EFFECT OF IMPACT AND VIBRATION ON QUALITY AND DAMAGE IN THE BRITISH STRAWBERRIES

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ABSTRACT

This study investigated the simulated impact and vibration tests on bruise damage and quality of the British strawberries from winter and summer cultivations. The actual transport of food products was also monitored for the vibration and temperature levels in the city and highways.

The winter cultivation produced a superior overall quality of 'Elsanta' and 'Sonata' strawberries compared to the summer cultivation. 'Sonata' fruits were more sensitive to vibration damage in the summer cultivation.

The packed strawberry punnet of 250 g was tested in impact and vibration tests. The maximum drop height at 750 mm gave a significantly larger wet bruise level of around 40% than other drop heights ($p \leq 0.05$). The simulated vibration investigated the three frequencies and three exposure times plus control. The vibrated fruits from the most severe of 5 Hz (1.1 *g*) for 150 sec had significantly higher wet bruises (50-60%) than for other treatments ($p \leq 0.05$). The bruise damages increased for both simulated tests after storage at 10^{o}C, 70±5% RH for 3 days.

The EC value gave a significantly stronger correlation with wet bruise and severity score as compared to puncture, compression and respiration rate measurements ($p \leq 0.01$). The EC method is suggested for use as a rapid indicator and a predictor for the bruise assessment of strawberries.

The vibration and air temperature levels in the refrigerated truck and semi-trailer were monitored. The overall peak frequency of power density was often found at 10-14 Hz. The vertical vibration was the dominant direction during the road transport. The rear-top position gave a stronger root mean square acceleration value. A gradual increase of vibration level occurred after the first drop in city distribute as well as for a smaller load. The range of temperature during food transport was around 2 to 8^{o}C with a set point at 3^{o}C.

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ABBREVIATIONS

J	joule
kg	kilogram
g	gram
mm	millimetre
Hz	hertz
min	minute
sec	second
^{o}C	degree celsius
RH	relative humidity
g	acceleration
g_{rms}	root mean square acceleration
PD	power density
PSD	power spectrum density
X-axis	lateral vibration-axis
Y-axis	longitudinal vibration-axis
Z-axis	vertical vibration-axis
T-axis	total vibration-axis
km	kilometre
hr	hour
EC	electrical conductivity
µS	microsecond
TSS	total soluble solids
TA	titratatble acidity

L*	lightness
a*	red/green opponent colour
b*	yellow/blue opponent colour
h*	hue angle
C*	chroma
MAP	Modified Atmosphere Packaging
r	correlation coefficient
DMRT	Duncan’s multiple range test
SE	standard error

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Strawberries (*Fragari*a x *ananassa* Duchesne) are widely grown in the temperate zone the world (Hancock, 1999). Recently, the estimated world production of strawberries was over 4.51 million tonnes worldwide in 2012. The US is the leading producer country (30.26%), followed by Mexico (7.98%), Turkey (7.82%), Spain (6.42%), and Egypt (5.36%), respectively. The UK was the twelfth strawberry-producing country, accounting for 2.12% of the total world production, according to the Food and Agricultural Organisation of the United States (FAO, 2014). Also, strawberries are among the top five most important British fruits in the market, along with apples, pears and raspberries based on large production and/or economic importance (Department for Environment Food and Rural Affairs, 2013). In the supply chain of the British strawberries, the strawberry losses are approximately evaluated 8-12%, particularly 2-4% at the retail market (Terry *et al*., 2011). In addition to the postharvest losses, the quality of fruits is also potentially influenced by the preharvest factors such as cultivar, mineral nutrition, irrigation and crop load (Crisosto and Mitchell, 2002).

The major physical damage of fresh fruits is caused by impact, vibration (abrasion), compression and punctures, resulting in structural, tissue and cell failure, leading to an increase susceptibility to decay and rot (Li and Thomas, 2014). The impact damage is indicated as the most severe damage of fruit handling (Van Zeebroeck *et al.*, 2007a). The impact energy is typically calculated from the drop height and fruit mass (Ruiz-Altisent and Moreda, 2011). Also, the bruise level of strawberries is strongly related to impact energy (Holt and Schoorl, 1982) and differs depending the impact surface (Kitazawa *et al.*, 2014). The vibration level during the actual transport or simulated test is presented in acceleration, frequency and power density (Berardinelli *et al.*, 2005; Lu *et al.*, 2010a).

In the Japanese studies of vibration effects strawberry bruise, the vibration condition of the actual transport was accelerations (0.02-0.18 *g*) and frequencies (3.35, 7 and 13.5 Hz) to cause vibration damage (Kojima *et al.*, 1999), whereas the simulated condition of strawberry had a higher acceleration (1.2-1.6 *g*) and a lower frequency (5 Hz) than the actual transport. Therefore, there is a wide range of vibration conditions that are a cause of vibration damage in strawberries. Most studies in the field of vibration level during transport have focussed on the position in the vehicle and the vibration levels varied in the different positions in the vehicle (Hinsch *et al.*, 1993; Soleimani and Ahmadi, 2014). Moreover, controlling cool temperature of fresh produce is important for its delivery to consumers. The appropriate temperature is necessary to retain produce in a good condition for food safety (Aung and Chang, 2014). In the case of mixed load, the shipment temperature should be controlled between wholesalers and customers with various transport options, multi-compartment trucks and mini-containers or insulating covers (LeBlanc and Hui, 2005). The variation of air temperature depends on the position in the refrigerated truck or semi-trailer (Hui *et al.*, 2006; Pelletier *et al.*, 2011) as well as the vibration level. The key to a reduction of strawberry bruising is by analysis of the preharvest and postharvest factors highlighted from the simulated tests and the actual transport.

1.2 STATEMENT OF PROBLEM

Food security and agricultural efficiency need the appropriate practice to minimize postharvest losses. The effect of external factors is investigated during harvesting, packing, transport and is suggested to improve handling methods for growers and other people concerning in the supply chain. Furthermore, the internal and external damages by a non-destructive method could be assessed and sorted into different damage levels (Li and Thomas, 2014). In the current study, bruise damage is one of the serious causes of strawberry losses. There are three possible strategies to reduce and evaluate bruising damage in the postharvest handling and transport of strawberries. The first strategy would be to analyse and identify various preharvest and postharvest factors which affect susceptibility of strawberries to bruise damage. The second strategy would be to integrate the understanding aspects in terms of engineering, packaging and postharvest technologies, thereby minimizing the consequences of bruise damage throughout whole their supply chain and financial return to the growers or producers. This third strategy would to be greatly assisted by a rapid bruise assessment of strawberries and also include the rot and mould detections, preferably nondestructive.

Most studies in the simulated tests of strawberries or other fruits have been carried out an individual fruit, not a whole punnet or package. The bruised strawberry fruits were occasionally presented at a bruise level by volume or area bruising, and visual score, which showed an inconsistent detection and a variation in the types of fruits, cultivars and maturity stages. Moreover, the actual transport has only been carried out in a single product or a single drop delivery with full load in the different positions of the vehicle. Nevertheless, there has been no published research on the effect of mixed load and partial load on the vibration level. Until recently, there has been no research published on the vibration level during transport on the UK roads.

In Thailand, Chiang Mai province in the northern region is the main location for strawberry production in Thailand due to an optimum average temperature (16-20^{o}C) as it is at 800 metres above mean sea level. The restricted area of production means the strawberry supply in Thailand is limited to the domestic market. Most tropical fruits in Thailand are produced under high temperature and humidity climates. Strawberry is the major example of temperate fruits in Thailand, which links to studies of its postharvest and supply chain in the UK. There has been no published research on impact and vibration studies of strawberries in Thailand. Moreover, the subject of this dissertation will contribute to the further study in strawberries, berries and tropical fruits.

1.3 AIMS AND OBJECTIVES

For both the summer and winter cultivations, this study was carried out to determine the quality and bruise of 'Elsanta and 'Sonata' strawberries after the simulated impact and vibration tests in the postharvest laboratory, Writtle College. The actual transport had vibration levels monitored and tracked shipment during transport on the London and Manchester routes, which departed from Reynolds Catering Supplies Ltd, London.

The specific objectives of this dissertation were to:

a) evaluate the effect of drop heights on the quality and the impact bruise of 'Elsanta' and 'Sonata' strawberries after storage at low temperature and grown in both winter and summer seasons
b) evaluate the effect of frequencies and exposure times on the quality and vibration bruise of 'Elsanta' and 'Sonata' strawberries after storage at low temperature and grown in both seasons
c) develop a nondestructive method for the bruise assessment in strawberry damage as use the rapid and accurate methods
d) investigate the vibration level and air temperature in the different positions in the refrigerated trucks on the city streets in the London shipments, and the semi-trailers on highways in the Manchester shipments.

1.4 HYPOTHESES

In particular, this dissertation will examine the eight research questions from the three main experiments which are impact test, vibration test and the actual transport of food shipments:

a) It is expected that there will be a higher level of impact and vibration damages on summer cultivation crops of 'Elsanta' and 'Sonata' cultivars.

b) It is expected that there will be no difference in impact and vibration damages between 'Elsanta' and 'Sonata' cultivars.

c) In this impact test, an increase drop height will give an increase in impact bruise for 'Elsanta''and 'Sonata' cultivars from the winter and summer cultivations after cool storage.

d) In the vibration test, an increase in frequency will give more bruising after cool storage for both cultivars.

e) It is also expected that greater vibration time after storage will give greater vibration bruise for all frequencies.

f) It is expected that a non-destructive method of bruise assessment will be developed as the rapid and accurate methods.

g) In the actual transport of food shipments, it is expected that the location of the consignment in the refrigerated vehicle will make a difference to the vibration level experienced.

h) It is expected that the temperature will remain uniform (± 1^{o}C) during shipment in refrigerated vehicles in city and long distance deliveries.

1.5 DISSERTATION STRUCTURE

a) The general introduction is given and discuss in Chapter 1.

b) Chapter 2 reviews the factors affecting on impact and vibration levels to fruit bruising and the strawberry quality changes after storage.

c) General materials and methods for plant materials and quality determinations of impact and vibration tests are outlined in Chapter 3. Further specific details are provided in Chapter 4 and 5.

d) The effect of drop heights on the quality and impact bruise of 'Elsanta' and 'Sonata' strawberries after storage at low temperature is examined in Chapter 4.

e) Determination of quality and vibration bruise from the different frequencies and exposure times of vibration test and the consequence of low temperature storage is also described in Chapter 5.

f) Chapter 6 investigates the vibration level and air temperature from the different positions in the refrigerated trucks and semi-trailers during food transport on the London and Manchester routes.

g) The final Chapter 7, the overall discussion evaluates results presented in the Chapter 4, 5 and 6 and implications for bruise assessment, preharvest and postharvest factors in handling operation and transport of strawberries. It also outlines the opportunities for further research studies.

CHAPTER 2

LITERATURE REVIEW

2.1 BRITISH STRAWBERRY PRODUCTION

2.1.1 Strawberry

Strawberry is an aggregate fruit with the enlarged receptacle (edible portion) as a psuedocarp, while achenes are the real one seed-fruit by combining seed and ovary tissue on the epidermal layer (Perkins-Veazie, 1995). Strawberry fruit is defined as a non-climacteric fruit (Will *et al*., 2007). Depending on cultivars and environmental conditions, strawberry fruit cv.'Elsanta' develops to a full red colour stage within 24-28 days after anthesis in greenhouse production (Terry *et al*., 2004). At the ripening stage, the maximum total soluble solids (TSS) level of 'Chandler' strawberry was around 28 days, whereas there was a little change in titratable acidity (TA) level. Thus the highest sugar: acid ratio occurred between 28 and 35 days as represented in the best quality attribute for consumption (Montero, 1996).

'Elsanta' and 'Sonata' cultivars can supply to the UK market for about 8 months of each year (Fresh Produce Journal, 2012) (Figure 2.1). The major fruit characteristics of 'Elsana' cultivar (June bearing cultivar) are medium size, firm fruit, orange-red colour (Terry, 2012) as well as the excellent shelf-life that make it popular with supermarkets (RW Walpole, 2014). 'Sonata' cultivar is a product of a cross-pollination between the seed of 'Elsanta' cultivar as the female and the pollen of 'Polka' cultivar as the male from the breeding program in Wageningen, the Netherland (Meulenbroek, 2007). 'Sonata' fruit is the second most widely planted June bearing cultivar, and produces a bright and glossy fruit with desirable flavour. However, this cultivar has less firmness and is more susceptible to bruising and ripening in the hot weather as compared to 'Elsanta' cultivar (RW Walpole, 2014).

Figure 2.1: The fruit characteristics of 'Elsanta' and 'Sonata' cultivars. *Source*: Chaiwong (2015).

2.1.2 Strawberry production in the UK

British strawberries accounted for approximately 24% of the total volume of home production fruits in 2014. For the soft fruit industry, strawberries have been the greatest home production (73%) when compared with blackcurrants (12%) and raspberries (9%). During the years 2013-2014, the volume and value of home production increased by 10% and 12%, respectively, while the demand for imported strawberries has had a gradual increase during the five years 2010-2014 (Table 2.1) (Department for Environment Food and Rural Affairs, 2014). In winter and spring seasons (November to May), the imported strawberries come from Spain, Morocco, Egypt and Israel (British Summer Fruits, 2012).

Over a 90-year period, the growth of the British strawberry industry has increased gradually and this has accelerated. Since 1996, the growing system in polytunnels has been widely introduced for strawberry cultivation due to the main three aspects of profitable crop protection. The three aspects are the protection from rain and grown under high temperatures, controlling product fluctuations in annual yields and the extension of harvesting season from 6 weeks to 6 months. In strawberry production with polytunnels, large farm enterprises (approximate 80% of strawberry crop area) gave a higher yield than small farm enterprises by 7.7 tonnes ha^{-1} (Calleja *et al.*, 2012). The main areas of strawberry production are located in Kent and an in oval zone in the West Midlands from the bottom of Herefordshire to the top of Staffordshire (Williams *et al.*, 2008).

Table 2.1: The strawberry supply and value in the UK market from 2010 to 2014 (Department for Environment Food and Rural Affairs, 2014).

Supply/Value	**2010**	**2011**	**2012**	**2013**	**2014**
(Thousand Tonnes)					
- Home Production	95.7	101.9	94.8	94.4	104.4
- Imports	38.1	47.1	49.7	46.3	49.0
- Exports	0.4	0.3	0.3	0.7	1.0
Total Supply	**133.4**	**148.7**	**144.2**	**139.9**	**154.4**
Value (£ Million)					
- Home Production	238.9	245.2	223.4	217.8	244.1
- Imports	95	120	123	118	130
- Exports	1.4	1.0	0.8	2.0	2.2
Total Value	**287.3**	**297.2**	**275.2**	**275.8**	**376.3**

2.1.3 Strawberry market and consumer behaviour

For the retail market, it is estimated that around 80% of the UK fruit is sold through the leading four marketing agents (English Food and Farming Partnerships, 2010). The smaller-scale strawberry enterprises have been suffering from changes in the market, which is now dominated by supermarkets. The smaller-scale enterprises are increasingly losing market share to supermarkets (Calleja *et al*., 2012). During the main strawberry season (Mid-June to September), over 60% of respondents buy between 80-100% British strawberries. These high percentages of respondents indicated a greater demand to buy the British strawberries in season, an especially powerful driver from supermarkets (Defra Food and Farming Group, 2011).

2.2 POSTHARVEST LOSSES OF FRESH PRODUCE

Postharvest losses commonly consist of qualitative and quantitative losses. Qualitative losses of fresh produce are more difficult to measure than quantitative losses because of the variation of quality standards and consumer preferences among countries and cultures. In developing countries, the reduction of quantitative losses is much more important than qualitative losses, whereas a greater percentage of postharvest losses are expressed mainly in terms of consumer dissatisfaction with quality of fresh produce in developed countries (Kader, 2005). A higher or more specific quality standard for supermarket requirement considers such as weight, size, shape and overall appearance, which lead to a problem of fresh produce losses (Stuart, 2009). The previous report is in agreement with that of Gustavsson *et al.* (2011), which showed over 40% of the food losses in the postharvest and processing stages for developing countries, and in the retail and customer stages for developed countries. Nevertheless, in the estimation of global food losses and waste, South and Southeast Asia provided the lowest food losses per capita (120 kg/year), while Europe and North-America had the highest volume (280 to 300 kg/year) (Figure 2.2).

There are two methods of postharvest loss estimation: either to evaluate loss components or to elicit questionnaires from experienced people in postharvest system (Hodges *et al.* 2010). Total losses of fresh fruits and vegetables worldwide were assumed at around 30% (Kader, 2005). Recently, as shown in Table 2.2, the range of total waste from all regions was 43% to 72% of the supply chain of fruits and vegetables, especially from the North African, and West and Central Asian regions. The estimated waste in postharvest handling and storage was around 4% to10% of the total supply chain, which was lower volume than distribution, supermarket and retail stages (8% to 17% of total waste) (Gustavsson *et al.*, 2011). Therefore, based on the available data on postharvest losses, a reduction of fresh fruits and vegetable losses should be considered from postharvest handling right through the customer.

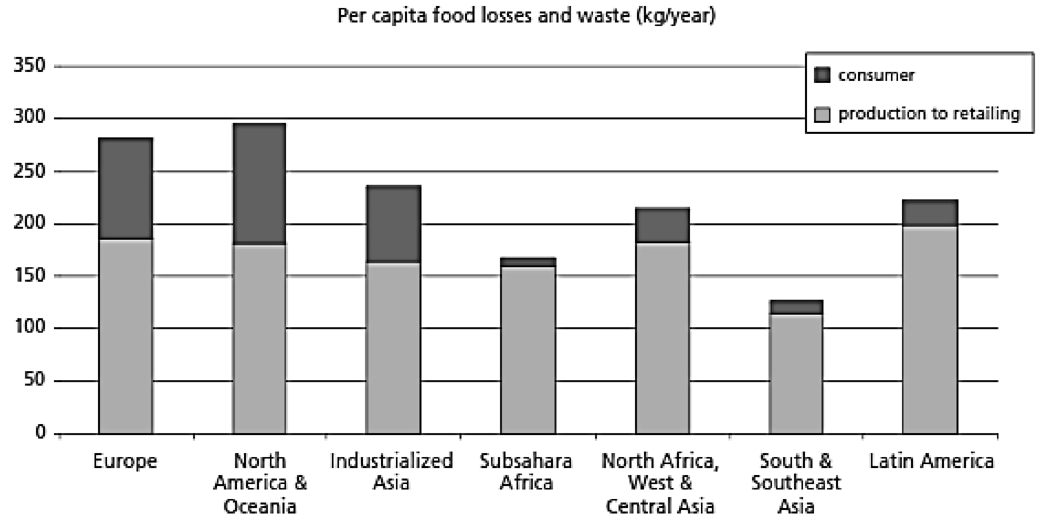

Figure 2.2: Per capita food losses and waste in different regions of consumption and pre-consumptions stages. *Source*: Gustavsson *et al.* (2011).

The typical causes of fresh produce losses are physiological deterioration, defects from mechanical injury, diseases and pests. As shown in Table 2.3, losses of fresh produce were caused by not only quality defects, but also labelling defects on packaging. The majority of quality and labelling defects were not giving the class or grade (37%) and rotting (23%). The damage percentage of quality defects and discoloured bruise were only 7% and 5%, respectively (Terry *et al.*, 2011).

Table 2.2: An estimated global waste percentage of fresh fruits and vegetables in supply chain from different regions (Gustavsson *et al.*, 2011).

Regions	**Agricultural production**	**Postharvest handling and storage**	**Processing and packaging**	**Distribution, Supermarket and Retail**	**Consumption**	**Total**
- Europe	20%	5%	2%	10%	19%	56%
- North America & Oceania	20%	4%	2%	12%	28%	66%
- Industrialized Asia	10%	8%	2%	8%	15%	43%
- Sub-Saharan Africa	10%	9%	25%	17%	5%	66%
- North Africa, West & Central Asia	17%	10%	20%	15%	12%	74%
- South & Southeast Asia	15%	9%	25%	10%	7%	66%
- Latin America	20%	10%	20%	12%	10%	72%

Table 2.3: The percentage of quality and labelling defects (Terry *et al.*, 2011).

Quality defects	**%**	**Labelling defects**	**%**
Rotting	23	No class/grade stated	37
Damage	7	No identity of the packer/dispatcher	22
Bitter Pit	6	Product not stated	10
Discoloured Bruise	5	Country of origin not stated	8
Not clean	5	Insufficient labelling	6

2.2.1 Postharvest losses of strawberries

The serious causes of strawberry loss were mould and rot, a poor cool chain system, mechanical damage and differences in specification between different suppliers. The UK research by Waste & Resources Action Programme (WRAP) reported the total of strawberry losses from field to retail market as 7.5-11.5%. In this case study, strawberry losses occurred as follows: 2-3% at the field, 1% at the grading stage, 0.5% at the storage, 2-3% at the packing stage and 2-4% at the retail market (Terry *et al.*, 2011). In a different study, the cool chain system for strawberries was greatly affected by temperature, with lower losses of around 5% at low temperature as compared to 65% with ambient conditions during truck transport (Ho, 2006).

Bruise damage and grey mould rot were the most common causes of serious strawberry losses during transport. The study of Ceponis *et al.* (1987) investigated strawberry disorders in 1,777 strawberry shipments to New York market during 1972-1987. Mechanical injuries caused bruise damage and leaky fruit in the affected shipments of around 70% and 50%, respectively, while grey mould rot provided the highest frequency of strawberry losses at around 76%. Grey mould rot was significantly correlated with bruise damage and/or leaky fruit in this study. The recent research in the US of Macnish *et al.* (2012) studied the road transport of ‘Albion’ strawberries from Watsonville (California) to Jacksonville (Florida) or Atlanta (Georgia). After strawberry shipments with a duration of 2 to 5 days, the incidence of decay increased slowly to a low level (1.2%). For shelf-life, following 2 days at 20^{o}C, the average decay from 6 shipments increased rapidly to a high level (40%); however, there was a wide range of decay incidence from 9% to 82% for these shipments. The highest percentage of frequency in decay severity showed moderate discoloration and slight mycelium growth.

2.3 QUALITY OF STRAWBERRIES

Postharvest quality has various definitions and depends on academic and commercial groups, namely researchers, producers, consumers and consultants. In particular, researchers, producers and handlers mostly require specific quality attributes of fresh produce such as sugar (sweetness), colour or firmness. These quality attributes are described as customer requirements from the group of consumers, marketers and economists (Shewfelt, 1999). The decision and satisfaction of consumers to purchase fresh produce rely on the appearance, quality and food safety. The quality components are generally described as the appearance (visual), texture (feel), flavour (taste and smell), nutritional value and safety (Kader, 2002b).

The industry trade associations are increasingly concerned with the public's growing dissatisfaction over the flavour and texture of some fresh produce (Baldwin, 2014). At the present, the texture is a major perception by a consumer and much more important than the flavour (Shewfelt, 1999). In marketing and business of fresh produce, there are advantages of common grading standards from growers through to receivers at the final market, and can solve problems between consumers and sellers. The grading standards are also helpful for producers and handlers for the better preparation and labeling of fresh products (Kader, 2002c).

This section reviews the quality attributes of strawberries and strawberry standards, particularly the appearance, colour, size and defect. The other attributes also are described firmness, flavour (sugar and acid) and nutritional value at the different maturity stages. In the case of physical and chemical properties during storage, the quality changes of strawberries will be explained in the last section (section 2.8: strawberry storage).

2.3.1 Quality attributes

The quality attributes of strawberries generally consist of the appearance or visuality (red colour intensity, fruit size, free from defect and disease), texture, flavour (sugars, organic acids, phenolics and aroma volatiles) and nutritional values (Kader, 1991). In the recent past, flavour and appearance were the most critical of strawberry quality attributes (Cordenunsi *et al.*, 2003), particularly high sugar and acid ratio, firmness and colour characteristics (Mitcham, 1996, Shin *et al.*, 2008). Much of the current research on strawberry quality pays attention to food nutrition and safety (Giampieri *et al.*, 2012). During simulated handling, the limited salability of strawberries caused poor colour, softening, shriveling and bruising (Nunes *et al.*, 2003). Additionally, the appearance (mould and rot) can also encourage undesirable changes in firmness and bring to decrease shelf-life of strawberries (Cordenunsi *et al.*, 2003).

Survey studies in sensory evaluation of fresh strawberries were evaluated in Switzerland. For example, overall acceptance in six strawberry cultivars by 120 panellists was mostly reflected by sweetness and aroma attributes which were expressed as total sugar levels and volatile compounds. No significant correlation was found in acidity, firmness, juiciness or odour (Azodanlou *et al.*, 2003). Likewise, a larger scale study in the freshness of strawberries was investigated by Ṕeneau *et al.* (2007). Three groups of panellists were divided into 167 consumers, 7 experts and 12 descriptive panellists. The definition of strawberry freshness for consumer perception was described as appearance, odour, flavour, and texture (hand and mouth). The best predictor of consumer perception in strawberries were appearance (bruise and shiny), sponginess, fermentation flavour and juiciness, followed by firmness (hand), odour and firmness (mouth).

As shown in Table 2.4, the major characteristics of fresh strawberries are described as appearance, texture and flavour. The important attributes of strawberries are freedom from such as defects, juice leakage, spongy, bitterness and fermentation flavour (Mitcham 1996; Ṕeneau *et al.*, 2007). In addition, visual rating scores and most severity used a simple 5-point scale, except the severity rating by Macnish *et al.* (2012) (Tables 2.5 and 2.6). As shown in Tables 2.5 and 2.6, either the acceptable visual score (score 3) suggested to have a maximum 5-20% of skin damage or discoloration surface, or the moderate level of severity (score 3) is indicated by slight mycelium growth (Macnish *et al.*, 2012; Nunes *et al.*, 2005b; Shin *et al.*, 2008). Thus, the acceptable visual score (score 3) varied in percentage of bruise and disease levels. Another visual rating scale is colour based on lightness intensity on strawberry surface. The range of visual scores is graded from 1 to 5 levels, such as 1 (three-quarter to full red), 2 (fully light red), 3 (fully dark red), 4 (very dark red (overripe)) and 5 (extremely overripe brownish-red/purple). Nunes and Emond (2007) reported In the previous studies, therefore, the important criteria of severity and visual rating in strawberries are skin damage, discoloration and mould.

Table 2.4: The important characteristics of a fresh strawberry (Mitcham 1996; Ṕeneau *et al*., 2007).

Characteristics	**Description**
Appearance	Degree of ripening: colour (not very red)
	Absence defects: bruise, decay and shriveling
	Absence juice leakage
	Surface: glossary, absence of water loss
	Brighter inside as outside
	Sepals: not faded
	Odour: absence fermentation odour
Texture	Hand: firm, elastic
	Mouth: firm, juicy, not spongy
Flavour	Not very sweet (high sugar and acid to be a good flavour)
	No bitterness
	No fermentation flavour

Table 2.5: The visual rating score of an individual strawberry fruit.

Score	Shin *et al.* (2008)	Nunes *et al.* (2003)
1	Unacceptable (>50% surface showing skin damage or discoloration)	Very poor (extremely overripe, wilted and dry calyces) (leaky fruit and partially or entirely rotten fruit.)
2	Bad (20-50% surface affected)	Poor (very soft, bruise, overripe and decay) (wilted and dry calyces)
3	Acceptable (5-20% surface affected)	Fair (minor signs of softness and shriveling) (visible bruise with no visible decay)
4	Good (up to 5% surface affected)	Good (firm with some small bruise)
5	Excellent	Very good (firm and turgid) (no signs of bruising, shriveling and decay)

Table 2.6: The severity score of an individual strawberry fruit.

Score	Macnish *et al.* (2012)[a]	Nunes *et al.* (2005b)	Fischer *et al.* (1992)
0	No visible	n/a	n/a
1	Slight brown discoloration	No visible changes in tissue, convert to 0%	Undamaged (no abrasions or 2 bruises less than 2 mm in diameter)
2	Moderate brown discoloration	Slight brown discoloration of the tissue, convert to 25%	Slightly damaged (no abrasions or 4 bruises less than 2 mm in diameter)
3	Slight mycelium growth	Slight to moderate mycelium growth, convert to 50%	Moderately damaged (less than 25% of surface bruised)
4	Moderate mycelium growth	Moderate to heavy mycelium growth, convert to 75%	Severely damaged (bruise penetrates the fruit surface)
5	Extensive sporulation	Characteristic sporulation, convert to 100%	Very severely damaged (whole fruit bruised, mould or pieces of fruit missing)

n/a is not available data. [a] Severity rating score (0 to 6 levels).

2.3.2 Temperature during cultivation affecting strawberry quality

Preharvest factors depend on specific cultivar and growth or development sensitivity. The cultivar is an important factor affecting yield, taste, quality and shelf-life of postharvest in horticultural products, including the incidence and sensitivity of decay. Also, environmental conditions during growth and development of fruits influence on their qualities (Crisosto and Mitchell, 2002). According to a complex interaction in preharvest factors, there has been little research conducted on the effect of preharvest factors on postharvest quality of strawberries. For example, in terms of either temperature level or seasonal cultivation on strawberry's quality, a higher temperature directly influences the reductions of flower, fruit yield, fruit size, fruiting period (Ledesmat *et al*., 2008; Singh *et al*., 2007a). Also, a rise in temperature on the fruit surface of strawberries resulted in an increase of the ripening process (Palencia *et al.*, 2013) and in a significant reduction of fruit firmness (Pyrotis *et al.*, 2012). The strawberries from late cultivation had a lower total soluble solids (TSS) content than those from early cultivation due to a shorter period for sugar accumulation (Rahman *et al*., 2014). Thus, a reduction of firmness and sugar content is probably influenced by an unsuitable temperature during their production.

2.3.3 Harvesting and grading

Hand-harvesting has many advantages for fresh products with a wide range of maturity and a short shelf-life because of bruising and damage (Thompson, 2002c). For strawberry harvesting, the recommended maturity stage for most fresh market is three-fourths red colour of fruit which then has a longer shelf-life than a fully ripe fruit. The harvested marketable fruit should have only a little stalk remaining which is called 'snap-picked' (Hancock, 1999). Another method of hand harvesting of strawberry fruit is called 'finger-picked by holding and picking a stalk of strawberry at around 15mm above the fruit between thumbnail and index finger (Strawberry, 2016).

The standards for strawberries are developed by a wide range of institutions by the Organisation for Economic Co-Operation and Development (OECD), the United States Department of

Agriculture (USDA), and United Nation Economic Commission for Europe (UNECE), including Rural Payments Agency (RPA). Most minimum requirements of strawberry standard define appearances, for example free damages from pest or disease and bruising, fresh and green calyx, ripening stage and fruit without washing (Figures 2.3 and 2.4) (OECD, 2005; USDA, 2006; UNECE, 2010; RPA, 2011).

The ripening stage of strawberries is graded by red colour surface. The pink or red colour of fruit surface must not be less than two-thirds of its surface for a ripe strawberry (Kader, 1999). For instance, the minimum red colour of U.S. No. 1 and No. 2 grades requires three-fourths and one-half of the strawberry surfaces, respectively (USDA, 2006).

The fruit size of strawberries is evaluated by the maximum diameter of the equatorial section. The size classification of strawberries is commonly graded into two classes such as 25 mm (superior quality) (Extra class by OECD, UNECE and RPA) or 19 mm (U.S. No.1), and 18 mm (Class I and II by OECD, UNECE and RPA) or 16 mm (U.S. No.2) (OECD, 2005; USDA, 2006; UNECE, 2010; RPA, 2011). Class II strawberries (marketable quality) are not only indicated by fruit size, but also classified by disease damage in the field. Class I fruits (good quality) are directly picked into a punnet for retail as called 'one punnet' system, which can reduce postharvest losses throughout the handling (Terry *et al.*, 2011).

Figure 2.3: Damaged, sunburn, severe and slight dry bruises of strawberries. *Source*: OECD (2005).

Figure 2.4: Disease symptoms and ripening stages of strawberries. *Source*: OECD (2005).

2.3.4 Mechanical damages and bruise

Fresh fruits are very susceptible to mechanical damages such as impact damage, abrasion (vibration), compression, and puncture damages during harvesting, packaging and transport. Impact damage occurs when fruit drops onto a surface with adequate force, while the dynamic impact of single fruit occurs in fruit-to-fruit impact and between packaging. Abrasion (vibration) is a dynamic movement of one fruit against another one, causing the removal of surface tissue. Compression damage causes an increase force onto the product with a smaller package during or after packing. Puncture damage causes the cut stem of fruit penetrate the skin of neighbouring fruit, which lead to a higher susceptibility to disease and weight loss with less shelf-life (Li and Thomas, 2014).

A bruise is a type of subcutaneous tissue failure with no rupture or breaking the skin of fruits and vegetables (Mohsenin, 1986). Bruise damage is commonly a mechanical damage of fresh produce and occurs in all stages of postharvest handling, particularly packinghouse operations, transport and storage (Opara and Pathre, 2014). The bruise damages from impact and vibration forces to the quality of fresh produce are explained in section 2.4 (Impact damage to fresh produce) and section 2.6 (Vibration damage to the quality of fresh produce).

2.3.5 Electrical conductivity (EC)

The estimation of membrane permeability is commonly measured by a solute leakage from plant tissue, which indicates genotypic variation and environmental stress. Electrical conductivity (EC) measures directly net ion efflux and has less vulnerability (Whitlow *et al.*, 1992). The EC measurement is useful to estimate cell membrane integrity from mechanical damages, chilling injury and fruit ripening (Saltveit, 2002; Ahmed *et al.*, 2010; Deng *et al.*, 2005; Jiang *et al.*, 2001; Milczarek *et al.*, 2009; Zhou *et al.*, 2007).

Measuring the changing electrical conductivity (EC) is a possible technique to determine fruit bruise from impact and vibration stresses. So far the EC method has not been applied to strawberry bruise from impact stress. The electrical conductivity (EC) method was used in the bruise determination from impact test in bananas (Bugard *et al.*, 2014) and tomatoes (Lee *et al.*, 2007). In the evaluation of strawberry damage, Jiang *et al.* (2001) examined strawberries cv. 'Tayonoka' at a vibrating frequency of 5 Hz. Two scenarios were examined under 1.4 *g* for 20 to 160 sec and 1.2 to 1.6 *g* for 40 sec. The conductivity was significantly correlated to the percentage of pared fruits or the damage index of strawberries. The electrical conductivity value decreased after storage at 25^{o}C for 2 days. In contrast to earlier results, Zhou *et al*. (2007) reported that the electrical conductivity of 'Huanghua' pear skin increased during storage at 23^{o}C for 36 days after the actual truck transport, particularly with reusable plastic containers (RPCs) in the rear top level. However, there has been little analysis of electrical conductivity to strawberry damage after both impact and vibration tests.

2.3.6 Postharvest diseases

The most serious loss of strawberries is caused by postharvest diseases, namely grey mould, Rhizopus rot, and Mucor rot. *Botrytis cinerea*, a sexual state, causes grey mould or Botrytis rot which is the most important postharvest disease of strawberries during the refrigerated storage and transport conditions (Sommer *et al.*, 2002). The infected fruits turn dull pink to brown and are covered with dry and greyish spores (Figure 2.5) (NSW Agriculture, 2004; Don, 2015a).

Rhizopus rot or leak rot, caused by *Rhizopus stolonifer*, may develop into the ripe fruit in the field and losses are primarily found after harvest (Sommer *et al.*, 2002; Don, 2015b). This fungus cannot grow at lower temperature than 5^{o}C (Mitcham, 2007). The other pathogens are *Mucor piriformis* Fischer and *Mucor hiemalis* Wehmer which cause Mucor rot and resembles Rhizopus rot. The most remarkable difference is the ability of these pathogens to grow below 0^{o}C while the growth of Rhizopus rot does not occur in this condition (Sommer *et al.*, 2002).

Figure 2.5: Botrytis rot (*Botrytis cinerea*). *Source*: Don (2015a).

2.3.7 Flavour (sugar and acid)

The chemical compositions of berry fruits vary depending on cultivar, growing area, maturity stage, storage conditions (Talcott, 2007). Maturity stage is an important factor in strawberry quality and plays a key role in its flavour. The good flavour of strawberries should contain high sugar and acid contents (Mitcham, 1996). Likewise, Cordenunsi *et al.* (2002) mentioned that the strawberry taste is a complex phenomenon which correlates to acids and volatiles; therefore it is not possible to explain the sweetness from sugar content based only on chemical analysis. Sugar is usually the main component of total soluble solids (TSS) and measured TSS concentration of an extracted juice sample using a refractometer gives ^{o}Brix or % unit. Acidity (titratable acidity; TA) is analysed from a sample of an extracted juice by titration with NaOH solution to a colour change of the pH indicator (phenolphthalein) at a pH level of 8.1 (Will *et al.*, 2007). Kader (1999) recommended that the minimum total soluble solids (TSS) and maximum titratable acidity (TA) contents for an acceptable strawberry flavour should be at 7% and 0.8%, respectively. For example, TSS, citric acid and TSS:TA ratio contents in 'Elsanta' cultivar were 5.7%, 0.94% and 3.8:1, respectively (Sturm *et al.*, 2003).

In the sugar analysis, fructose is the predominant sugar of strawberries (1.23 to 6.27%), followed by glucose (0.71 to 8.64%) and sucrose (0.01 to 2.27%), respectively (Talcott, 2007; Mahmood *et al.*, 2012; Ornelas-Paz *et al.*, 2013). For instance, 'Elsanta' strawberries at full red stage contained fructose (2.04%), glucose (1.69%), sucrose (0.44%) and xylose (0.1%) (Sturm *et al.*, 2003). On the change of maturity stage, the greatest fructose and glucose contents were found in the full red colour stage, while the highest sucrose content was found in the turning stage (Ornelas-Paz *et al.*, 2013). In the case of days from fruit set, the reducing sugar content (glucose and fructose) of 'Chandler' cultivar increased considerably until 35 days and related to the maximum TSS level at around 28 days (Montero, 1996). On the other hand, there was not a significant correlation between TSS and total sugar (fructose, glucose and sucrose) whereas the individual sugar contents (fructose and sucrose) were significantly correlated with TSS (Kafkas *et al.*, 2007). In the enzyme conversion, Talcott (2007) reported that the change of sugar compositions from sucrose to reducing sugar (fructose and glucose) showed an increase of invertase activity from the early stage through the full red colour stage. However, there has been little research about starch content during fruit development. For instance, a reduction of starch content in 'Elsanta' strawberries was reported as reducing from around 5.5 % dry weight (DW) to 0.2% DW during ripeing (Moing *et al.*, 2001).

TA content mainly contains organic acids and phenolic acids. Organic acids can maintain the changes of ascorbic acid and fruit colour by supporting stabilize anthocyanins. The pH level is often a poor indicator of fruit quality characteristics (Talcott, 2007). The major acid of strawberries is citric acid with the content range of 0.09 to 2.60% (Talcott, 2007; Mahmood *et al.*, 2012). The optimum maturity of strawberries (the highest TSS:TA ratio) was recommended to harvest between 28 and 35 days after fruit set. After fruit set for 21 days, the pH level of strawberries decreased gradually around 40%, whereas the TA levels minimally changed over the entire of mature period (Montero, 1996). However, the previous result of pH level differs from

Ornelas-Paz *et al.* (2013) report, the pH level of strawberries increased gradually from the white stage to the dark red stage.

2.3.8 Firmness

Most consumers desire a firmer strawberry which affects directly the susceptibility to physical and mechanical injuries (Kader, 1999). Fruit texture and consumer perception are correlated to changes in cell wall compositions and physical attributes. There are various methods to determine accurately strawberry firmness. Most penetration or puncture tests have been used by Instron instrument with probe size (3.2 to 7.49 mm), whereas the Texture Analyzer and the Lloyd instruments are particularly used in the scientific research (Døving *et al.*, 2005). The probe size directly affects firmness value. For the selection of probe or plunger size, Hietaranta and Linna (1999) suggested that a smaller probe for strawberry penetration test would probably give more reliable results instead of a bigger probe size with a diameter of 6.4 mm. Mitcham *et al.* (1996) also recommended that probe size for the firmness test of strawberries was 3 mm. Therefore, the probe size for puncture testing in strawberries is suggested as a diameter range of 4-8 mm (flat or blunt end). A depth of penetration should not be more than 5 mm (Døving *et al.*, 2005). The method of firmness test also related to the quality and sensory attributes. Kader (1991) found a good relationship between penetration and shear force, and between sensory firmness and both firmness methods. Testoni *et al.* (1989) reported that a compression test appeared to be more reliable than a pressure test (puncture test) to evaluate the susceptibility of rotting.

The firmness of strawberries varies in maturity stage, fruit size and internal fruit temperature. Azodanlou *et al.* (2004) investigated the degree of ripening on firmness with shear test equipment. From the white stage through the dark red stage, there was a reduction of firmness around 75%. The previous finding is in agreement with the result of Ornela-Paz *et al.* (2013) with two ripening stages which showed the firmness of 'Albion' strawberries decreased considerably around 90% with ripeness. Moreover, Døving and Måge (2002) found that there was no a significant correlation between firmness and total soluble solids (TSS) content, whereas TSS content was extremely variable between individual fruits. There was no correlation between firmness and fruit weight by the Texture Aanlyser. Therefore, the variable firmness of strawberries depends on strawberry cultivar, maturity, probe size, method of testing and fruit size.

2.3.9 Nutritional values (ascorbic acid and anthocyanins)

Over the past 15 years, there has been a dramatic increase in bioactive compounds and antioxidant capacity studies of strawberries. Ascorbic acid is the most essential compound and accounts for over 30% of total antioxidant capacity followed by anthocyanins (25% to 40%) (Giampieri *et al.*, 2012). Strawberries contain the highest ascorbic acid content (58.8 mg/100g) when compared with raspberries (26.2 mg/100g), blackberries (21 mg/100g) and blueberries (9.7 mg/100g) (U.S. Department of Agriculture, 2012). Ascorbic acid increased rapidly through the ripening period (Montero *et al*., 1996) and the full red colour stage of strawberry also contained the highest ascorbic acid level when compared to the other stages (Kafkas *et al*., 2007; Mahmood *et al.*, 2012; Ornelas-Paz *et al.*, 2013).

The changes of anthocayanin concentration during strawberry ripening correlated to external turning colour. Hue angle (h*) of strawberries particularly represented a good correlation with anthocyanin content (r = 0.8306) (Fredericks *et al.*, 2012). Montero *et al.* (1996) found that the amounts of total anthocyanins increased continuously to a maximum level (80 mg/100g) at 35 days after fruit set. This finding is in agreement with Ornelas-Paz *et al.* (2013) who report that total anthocaynin content in ‘Albion’ strawberries increased from 0.9 to 56.4 mg/100g during ripening.

2.4. IMPACT DAMAGE TO FRESH PRODUCE

There are two typical methods for impact testing: to drop the fruit from a specific height onto the impact surface or to mount the fruit with a pendulum impactor. In the case of fruit dropping from a specific height, the impact energy *(E)* of the impact test is calculated by the following equation, $E=mgh$, where m denotes fruit or sample mass; g denotes acceleration of gravity (9.81 m/s^2); h denotes drop height (m) (Ruiz-Altisent and Moreda, 2011). A pendulum impactor requires swinging a part of the fruit from the different drop heights onto a hard surface (Opara and Pathare, 2014). However, this chapter focusses on the impact method by a drop test. Also, this chapter describes the effect of impact energy and fruit shape on bruise damage by impact test. The drop height and impact surface materials affect bruise damage and fruit quality.

2.4.1 Impact energy and energy absorbed to bruise damage

There are a great number of published studies describing the relationship between impact energy and energy absorbed as well as damage level. A strong linear correlation between impact energy and bruise volume was reported for many fruits such as strawberries (Holt and Schoorl, 1982), apples (Schoorl and Holt, 1980; Brusewitz and Bartsch,1989; Unuigbe and Onuoha, 2013), peaches (Maness *et al.*, 1992), pears (Sinobas *et al.*, 1991), bananas (Kajuna *et al.*, 1997), olive fruits (Jiménez- Jiménez *et al.*, 2013), coconuts (Kitthawee *et al.*, 2011) and pomegranates (Shafie *et al.*, 2015). An increase of bruise volume is associated with an increase of drop height and fruit mass (Jiménez- Jiménez *et al.*, 2013). For instance, Reza (2013) found that increasing the height from which peaches were dropped from 500 to 1500 mm increased the average bruise area by around 15%.

Moreover, the material surface affects the absorption of impact energy. For example, a double-wall corrugated fibreboard box can absorb much more impact energy than a single-wall box in research by Lu *et al.* (2010b); therefore, a double-wall box showed a lower fruit bruise damage of than a single-wall one. This research is in agreement with the study by Reza (2013), which showed the impact of peach fruits onto a rubber surface gave a lower bruise area than impact onto a steel surface because of the higher energy absorbing property of rubber.

Despite this, a neighbouring fruit could absorb impact energy and this could be related to energy absorbed and bruise volume, particularly in apple fruits, when it is called apple-to-apple. Pang *et al.* (1992) found that the total bruising volume for both apples was a linear correlation with the energy absorbed. However, Studman *et al.* (1997) suggested that the bruise area was not an appropriate index of total bruise volume in apple-to-apple impacts due to the high variation in bruise depths.

2.4.2 Effect of fruit shape on impact bruise

A number of studies have examined the effect of fruit shape on bruise damage from impact tests. Most reports of fruit shape referred to the radius of curvature, at which a small radius of curvature gave more bruise damage, area or volume than a large radius of curvature in pomegranates (Shafie *et al.*, 2015), kiwifruits (Ahmadi, 2012), peaches (Ahmadi *et al.* , 2010), apples (Van Zeebroeck *et al.*, 2007a; Zarifneshat *et al.*, 2010). An increase of bruise damage is also associated with a higher energy absorbed at a small radius of curvature (Ahmadi, 2012). For example, Zarifneshat *et al.* (2010) reported in 'Golden Delicious' apples that at the high impact energy (0.19 J), the bruise volume of an apple with a smaller curvature radius (34 mm) was 27% higher than that for an apple with a larger curvature radius (46 mm). In contrast, at the check area of pomegranates, a high radius of curvature provided high susceptibility to any bruise due to being extended over a large area. The check region and firmness had less correlation coefficient value (r = 0.554) than calyx shoulder and firmness (r = -0.817) (Shafie *et al.*, 2015). Moreover, the larger fruit size or mass affected higher bruising in olives (Jiménez- Jiménez *et al.*, 2013) and apples (Golacki *et al.*, 2009). Golacki *et al*'s. (2009) results agreed those for pear fruits, which had more elongated shape and led more susceptibity to bruising (Blahovec and Peprštein, 2005).

2.4.3 Drop height, impact surface and number of drops

The impact conditions of a drop test from the various heights and impact surfaces were summarized as shown in Table 2.7. Several studies investigating a drop test have been carried out on apple bruising. The apples were dropped from a height range of 50 to 1400 mm (Lu *et al.*, 2010a, b, 2012; Unuigbe and Onuoha, 2013). In an apple postharvest handling study, the potential drop heights at orchard were 600 mm through to the retail display with a drop height of 50-300 mm (Lewis *et al.*, 2008). Whilst the range of drop heights in a berry test from 50 to 1200 mm was also at a similar level in the apple test (Kitazawa *et al.*, 2014; Yu *et al.*, 2014). In the case of strawberry impact, the individual fruit or packed strawberries were dropped from 50 to 380 mm (Ferriera *et al.*, 2008; Kitazawa *et al*., 2014). The minimum height of peach, tangerine, and tomato fruits was carried out at approximately 500 mm (Reza, 2013; Vergano *et al.*, 1991; Montero *et al*., 2009; Idah *et al*., 2007).

There are a large number of published studies comparing or describing the impact bruising from different impact surfaces. The surface materials were paper (cardboard and corrugated fibreboard), metal or steel, rubber, wood, foam, hard plastic and rigid ceramic (Lu *et al.*, 2010a, b, 2012; Idah *et al.*, 2007; Reza, 2013; Montero *et al.*, 2009, Unuigbe and Onuoha, 2013). The steel or wood surface (hard material) caused the greatest bruising on the dropped fruits such as apples (Lu *et al.*, 2010a; Idah *et al.*, 2007), peaches (Reza, 2013), tomatoes (Unuigbe and Onuoha, 2013), kiwifruits (Mencarelli *et al*., 1996), and table olive fruits (Saracoglu *et al.*, 2011).

The bruise area or volume of impact on cardboard or corrugated fibreboard was less than on metal, wood, plastic and rubber (Lu *et al.*, 2010a; Kitazawa *et al.*, 2014; Idah *et al.*, 2007). For example, Kitazawa *et al.* (2014) studied the strawberry damage from drop heights of 50 to 300 mm and surface materials (a corrugated fibreboard sheet with ‘A’ flute or a silicon rubber sheet). The degree of damage on corrugated fibreboard was less than on silicon rubber, at around 12-18% of the height range of 200-300 mm. The thickness of corrugated fibreboard boxes was also studied by Lu *et al.* (2010b). The double-wall corrugated fibreboard box reduced the impact damage in packed apples as compared to the single-wall package. Another damage of papaya showed as skin injury from a drop height of 100 mm onto sandpaper, while the impact damage from a height of 750 mm onto a smooth steel plate led to internal injury without skin injury. Thus, the major cause of skin injury of papaya was from abrasion and puncture damage, not impact damage (Eloisa *et al.*, 1993). However, these previous studies were simulated and tested with a variety of surface materials. During the actual postharvest handling, the different surface materials also affected the damage of fresh produce. For instance, in potato research, Bishop *et al.* (2012) investigate the frictional damage from three material types. Rubber was the most appropriate material for handling potato tubers when compared with mild steel and plastic.

The number of drops onto an impact surface also influences fruit quality. For instance, an increase number of drops (8 drops) increased the respiration rate of mature green tomatoes around two fold when compared to control (no drop) (MacLeod *et al.*, 1976). On the other hand, Lu *et al.* (2012) examined a drop test of apple from heights of 50 to 300 mm onto a rubber surface for 1, 4, 8 and 12 times. There was not a significant difference in bruising area or volume for a different number of drops in the range of 50 to 100 mm and 200 to 300 mm. Regarding a multiple impact test and impact energy, Golacki *et al.* (2009) found that the first drop gave the largest impact energy, as well as the lowest rebound height, with the highest bruise energy, and then gradually reduced on permanent tissue deformation. The fourth drop showed a stable rebound height, which stabilized the bruise energy as called an asymptote level was an irreversible change of cell damage.

2.4.4 Impact bruise to fruit quality

The bruise characteristics from impact, vibration and compression had different patterns, which depended on fruits and fruit tissues (Chen *et al.*, 1987; Vergano *et al*., 1991; Underhill *et al.*, 1998); therefore it was quite difficult to quantify the bruise level (Underhill *et al.*, 1998). Another type of damage in fruits is compression damage, which was reported in strawberry bruise by Holt and Schoorl (1982). The results showed that a slow compression on strawberries gave more bruising than impact damage due to a compression force leading to a change of the cell dimension by cell wall fracture. Also, the strawberries had puncture damage from a shorter pedicle of neighbouring fruit in punnets (Terry, 2012) the same as the result of puncture injury in tomatoes in transit from greenhouse to consumer (Desmet *et al.*, 2003). Impact bruise has affected fruit quality such as fruit firmness, EC value, colour and respiration rate (Sinobas *et al.*, 1991; Lee *et al.*, 2007; Burton and Schulte-Pason, 1987; Sanford *et al*., 1991). The bruise incidence had a strong relation to fruit firmness, for example, for apples and persimmons (Sinobas *et al.*, 1991; Lee *et al.*, 2005). The bruise volume and firmness in apple impact had a significant correlation with a low correlation coefficient value (r = -0.20 to -0.45) (García *et al.*, 1995). A puncture force can be a good indicator for evaluation of peaches bruise by impact test (Hung and Prussia,1989).

There has been a little EC measurement of impact bruise in fresh fruits. Bugard *et al.* (2014) reported that the lowest impact energy (20 mJ) produced a visible bruise, which gave a significant difference in EC value of banana peel during ripening (r = 0.78). In impact bruised tomatoes, the enzyme activity of polygalacturonase (PGs) and EC value reduced during the first two days of storage at 20^{o}C after impact damage from a drop of 400 mm, and increased during ripening after 6 days (Lee *et al*., 2007).

After an impact test, the colour changes gradually developed in browning or in some cases increase in whiteness and may correlate to bruise damage (Samin and Banks, 1993; Lee *et al.*, 2005; Montero *et al.*, 2009). A reduction in firmness was not associated with the decrease in colour of persimmon bruising (Lee *et al.*, 2005). However, Samim and Banks (1993) studied the browning incidence in apple bruising after the drop test using a stainless steel ball onto the fruit surface. The lightness (L*) and hue (h*) values of bruised cortical tissue decreased while the chroma (C*) value increased gradually. The bruise recovery process was observed to fade and produce moisture loss after bruise damage within an hour. The bruise recovery process is supported by the research of Toivonen *et al.* (2007). The recovery process of the apple bruising may be improved at low temperature (1^{o}C) or inhibited at higher temperature (13^{o}C). In the case of a serious bruise, it is difficult to achieve any visible recovery in the bruising. For bruised blueberries, a drop test of lowbrush blueberries from a height of 1590 mm led to a major colour change as measured by h* (hue angle) from blue to blue-red, but was not associated with L* value. The colour changes of split blueberries in h* value may cause anthocyanin leakage from cell breakdown (Sanford *et al.*, 1991). Therefore, the parameter of colour attributes (L*, a*, b*, h* and C*) depended on bruise level and commodity, which related to cell structure and chemical positions of cells.

The CO_2 evaluation of blueberries, sweet cherries and cranberries was suggested as an indicator of bruise damage by harvesting and handling operation. The respiration rates of blueberries, sweet cherries and cranberries had similar patterns, which gradually declined after impact test and was definitely affected by the number of drops (Burton and Schulte-Pason, 1987; Massey *et al.*, 1982). Conversely, the pattern of respiration rate in mature-green tomatoes showed a gradual increase after drop test and reached to the maximum peak within 2 days at 20^{o}C, whereas the control fruits had that peak by day 7. Also, a 4-drop treatment that increased the respiration rate of tomatoes was around 35%, when compared with the control fruits (MacLeod *et al.*, 1976). Lee *et al.* (2007) found that the respiration rates of impacted tomatoes at the breaker, pink and light-red maturity were higher than undamaged tomatoes, particularly after an hour on day 0 at 20^{o}C. In terms of changes in chemical composition of bruised fruits, there was a little difference between intact fruit and bruised fruit. The impact test did not affect TSS content of lowbrush blueberries, while TA content increased with the impact test from 530 mm to 1590 mm during storage (Sanford *et al.*, 1991). In contrast, there were not significant differences in TSS, TA and TSS:TA from impact damage of tomatoes (Lee *et al.*, 2007).

Table 2.7: The summarized conditions of a drop test from different heights and impact surfaces.

Commodity	Dropping height (mm)	Impact surface	References
Apple	50-300	- Rubber	Lu *et al.* (2012)
	50-500	- Double-wall corrugated fibreboard - Rubber - Wood*	Lu *et al.* (2010a)
	200-500 (5 times)	- Double-wall and single-wall corrugated fibreboard	Lu *et al.* (2010b)
	500-1400	- Foam - Cardboard - Metal - Wood*	Unuigbe and Onuoha (2013)
Peach	500-1500	- Steel* - Rubber	Reza (2013)
	310-910	- Steel (310 is a critical drop height)	Vergano *et al.* (1991)
Strawberry	50-300	- Corrugated fibreboard - Silicon rubber*	Kitazawa *et al.* (2014)
	130-380	- Solid aluminium	Ferreira *et al*. (2008)
Blueberry	600-1200	- Hard plastic	Yu *et al.* (2014)
Tomato	500-1400	- Foam - Cardboard - Plastic - Metal* - Wood	Idah *et al.* (2007)
Kiwifruit	300	- Steel* - Wood	Mencarelli *et al.* (1996)
Tangerine	400-1000 (2 times)	- Rigid ceramic	Montero *et al.* (2009)

* The impact surface gave the greatest impact bruise of fruits.

2.5 VIBRATION DURING THE ACTUAL TRANSPORT

2.5.1 Road transport

According to the UK guide list of trailers, there are in total 15 types of truck and trailer, classified by maximum gross weight and the number of axles (Department for Transport, 2003). In the UK, the maximum gross weight for an articulated vehicle is 44 tonnes (44,000 kg) gross (including truck, fuel and loading), consisting of up to 6 sets of axles. The maximum size of individual trailer is 16.5 metres long and 2.55 metres wide (HM Revenue and Customs, 2013). However, trailers in the United States (US) can have an exterior length of 16.2 metres and a width of 2.6 metres. The maximum gross weight is 36,288 kg with a loading capacity of around 18,100 to 20,400 kg (Thompson, 2002b).

In recent years, there has been increasing research interest in vibration levels during road transport. Many countries have been involved in these studies on vibration levels, such as Thailand (Chonhenchob *et al.*, 2010), Japan (Lu *et al.*, 2008), China (Zhou *et al.*, 2007), India (Singh *et al.*, 2007b), Sri Lanka (Ranathunga *et al.*, 2010), Spain (Garcia-Romeu-Martinez *et al.*, 2008), Brazil (Rissi *et al.*, 2008), and North America (Singh *et al.*, 2006). The varying vibration levels in truck transport depend on the position of the load in the vehicle or position of the pallet in the stack, payload, truck size, vehicle suspension, truck speed and surface condition (Berardinelli *et al.*, 2005; Garcia-Romeu-Martinez *et al.*, 2008; Jarimopas *et al.*, 2005; Lu *et al.*, 2010a; Singh *et al.*, 2006). In most cases, the truck vibration levels were analysed in terms of power spectrum density (PSD), acceleration (g) and root mean square acceleration (g_{rms}) values (Lu *et al.*, 2010a).

2.5.2 Acceleration (g), frequency and power spectrum density (PSD)

Vibration always occurs in the distribution chain because of transport and handling by the movement of products. The exciting force of vibration consists of two types: random and periodic vibrations. Vehicle vibration during transport is defined as random vibration. This differs from periodic vibration, which is a spring-mass system. For vehicle vibration during travelling, the vehicles are exposured to vibration at multiple frequencies. The acceleration (*g*) of vehicle vibration varies at each instant and is unrepeatable in the same pattern. As shown in Figure 2.6, a random vibration signal during transport is recorded on a truck floor (Marcondes, 2009).

In the case of a transport vehicle under high vibration conditions, the package will not be in contact with vehicle floor all the time, and then the package will move and hit the vehicle floor. The package movement results in magnitude of impact rather than vibration magnitude under large vibration conditions; therefore, the acceleration of impact is much higher than vibration. In these conditions, it should be noted that the vertical vibration value of a vehicle floor is higher than 1acceleration gravity (*g*) (Marcondes, 2009).

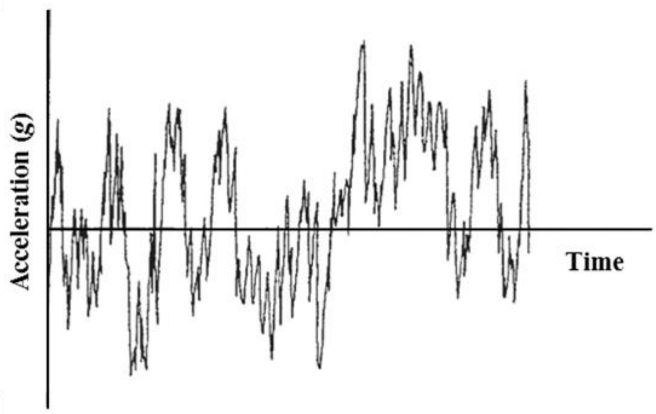

Figure 2.6: A typical random vibration represents acceleration (*g*) and time. *Source*: Marcondes (2009).

For most packaging applications, the calculation of power density (PD) level is normally referred and measured from the formula giving by Marcondes (2009).

$$PD(f)= \frac{1}{BW}\frac{\sum_{n=1}^{N} G_{rms,\ n}^{\ 2}\ (f)}{N}$$

PD at the frequency (*f*) is calculated as in the above formula and reported in unit (G^2/Hz) for random vibration analysis. *N* is the number of samples in the frequency and $G_{rms, n}$ is a root mean square acceleration of *n*th sample at the frequency (*f*). *BW* is normally bandwidth to 1 Hz.

However, it should be noted that there is also a large volume of published packaging studies that mention the power spectrum density (PSD) instead of power density (PD). Most published journals reported PSD value by computation from various commercial software programs. (Chonhenchob *et al.*, 2009, 2012; Ishakawa *et al.*, 2009, 2010; Ranathunga *et al.*, 2010; Rissi *et al*., 2008; Soleimani and Ahmadi, 2014, Singh *et al.*, 2007; Timm *et al*., 1996). High or low PSD level shows at which frequency; there is a strong or a weak point in each travelling vehicle (Singh *et al.*, 2006). The high PSD level at a specific frequency may show a vehicle problem; therefore, PSD represents the quality of road and/or vehicle (Marcondes, 2009). A PSD plot provides the monitoring of actual transport environment, which is an essential tool in assisting the simulated vibration condition in a laboratory (Singh *et al.*, 2006). For instance, the PSD value of the truck transport in Thailand and India was recommended to be at a frequency of 3-30 Hz (Jarimopas *et al.*, 2005; Singh *et al.*, 2007b, Chonhenchob *et al*., 2010) (Table 2.8). Three frequency ranges over a US interstate expressway were found to relate to the following sources: suspension (3-4 Hz), tyres (15-20 Hz) and truck floor (40-55 Hz) (Singh *et al.*, 2006) (Figure 2.7).

Table 2.8: Recommended PSD value at 3-30 Hz of frequency for truck transport in Thailand and India.

Frequency (Hz)	PSD (G^2/Hz)		
	Thailand Jarimopas *et al.* (2005)	**Thailand** Chonhenchob *et al.* (2010)	**India** Singh *et al.*(2007b)
3	0.400	0.007	0.01
10	0.010	n/a	n/a
12	0.020	n/a	n/a
20	0.020	n/a	0.0002
30	0.010	n/a	n/a

n/a is not available data.

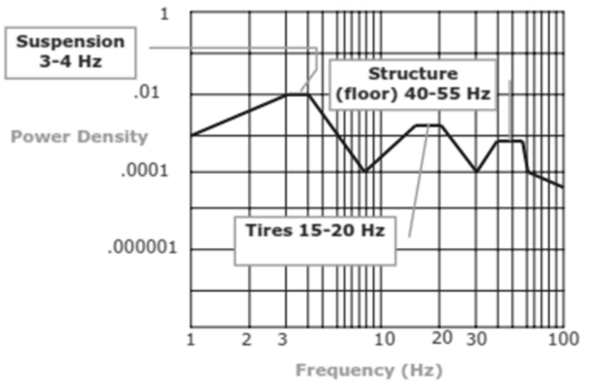

Figure 2.7: An actual PSD for a truck transport with leaf spring suspension. *Source*: Singh *et al.* (2006).

The greatest number of investigations into vibration levels was reported in Asian countries (Chonhenchob *et al.*, 2009, 2010, 2012; Ishakawa *et al.*, 2009; Zhou *et al.*, 2007). In Thailand, the vibration levels of truck transport in various vehicle types were explored. Not only was the vibration level in a truck observed, but also in a van and a pick-up. The highest PSD level during delivery testing occurred in 2-3 Hz in both vehicles (Chonhenchob *et al.*, 2012). The range of lowest frequency was 1-5 Hz, which caused by the vertical vibration measurement on highways (Chonhenchob *et al.*, 2009).

In a Japanese trial, the PSD peak for a truck transport was at 15 Hz, whereas the peak vibration of truck transport in Taiwan was found in a PSD peak at 2-3 Hz (Ishakawa *et al.*, 2009). For the Chinese and US shipments, the peak of PSD spectra was in the 2.5-4 Hz range (Hinsch *et al.*, 1993; Zhou *et al.*, 2007). The simulated testing and road transport were also studied in Italy by Barchi *et al.* (2002) and Berardinelli *et al.* (2005). The maximum of PSD level on Italian roads occurred in 10 to 16 Hz. Furthermore, Vursavuş and Özgüven (2004) found that the highest acceleration value was 0.25-0.50 *g* (5-10 Hz) and 0.50-0.70 *g* (10-15 Hz) during a truck transport in Turkey.

From the studies mentioned above, the vibration level varied in the type of vehicle, road condition in each country; overall, the frequency of the PSD peak could be classified into low and medium frequency ranges. The low and medium frequencies are 1-5 Hz and 10-16 Hz, respectively.

2.5.3 Direction of vibration (X, Y and Z coordinates)

A Cartesian coordinate is introduced at this stage as a frame of reference. The main axes are composed of X-axis (lateral vibration), Y-axis (longitudinal vibration) and Z-axis (vertical vibration) (Figure 2.8). Several transport studies investigating the vibration in all three directions have been carried out in order to obtain the maximum vibration level. The vertical vibration (Z-axis) represented the highest vibration level during monitoring levels in truck, van and rail shipments (Chonhenchob *et al.*, 2009, 2010, 2012; Lu *et al.*, 2010a; Rissi *et al.*, 2008). On the other hand, the longitudinal vibration caused more strawberry damage than vertical vibration under the simulated vibration test (Nakamura *et al.*, 2007b). Until recently, there has been a little research on how the vibrating direction affects fresh produce damage.

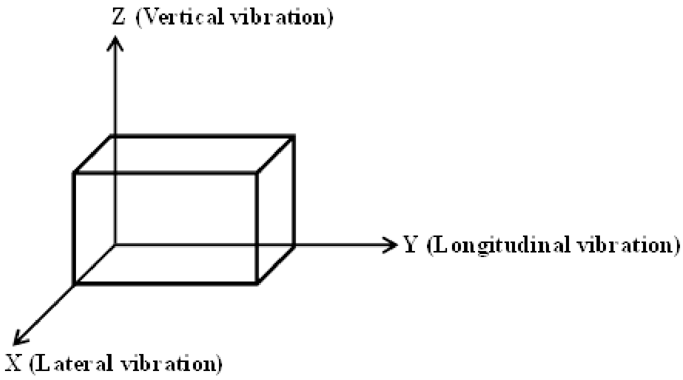

Figure 2.8: Three directions of vibration (X, Y and Z coordinates). *Source*: Saowapa (2015).

2.5.4 Factors affecting vibration levels during road transport

Factors found to be influencing different vibration levels have been explored in packaging studies. The vehicle characteristics were mainly observed in truck transport, for example:

1) position of the vehicle and the package along the stack (Barchi *et al.*, 2002; Berardinelli *et al.*, 2005; Hinsch *et al.*, 1993; Ranathunga *et al.*, 2010; Zhou *et al.*, 2007)

2) payload and vehicle size (Garcia-Romeu-Martinez *et al.*, 2008)

3) vehicle suspension (Garcia-Romeu-Martinez *et al.*, 2008; Singh *et al.*, 2006; Timm *et al.*, 1996)

4) speed and road surface condition also affected vibration levels in transit (Çakmak *et al.*, 2010; Lu *et al.*, 2010a).

2.5.4.1 Position of the vehicle and the package along a stack

Various studies have referred to the location of the package within the vehicle or how the height of its stack affects the vibration level. The positions were commonly compared at two or three locations such as the front, middle, and rear. The top, centre and bottom packages along the stack also affected the vibrating level, especially the top package. For instance, in the simulated vibration of pear, the top box in a pallet increased three to four times more than that level at the bottom box (Slaughter *et al.*, 1993). Additionally, the next chapter (vibration damage to the quality of fresh produce) will particularly describe the changes of fresh produce quality after vibration damage.

As can be seen from Table 2.9, levels of frequency and root mean square acceleration (g_{rms}) in different positions are summarized for various research studies. The rear position provided a higher g_{rms} value as compared to the middle or front position (Berardinelli *et al.*, 2005; Hinsch *et al.*, 1993; Soleimani and Ahmadi, 2014). These results are in agreement with Zhou *et al.* (2007) and Barchi *et al.* (2002), which showed the peak PSD spectra in the rear location.

The different locations of the package within the stack were determined as top, centre and bottom levels (Table 3.2). The top package had the greatest vibration level (g_{rms}), followed by the centre and bottom levels (Barchi *et al.*, 2002; Berardinelli *et al.*, 2005; Hinsch *et al.*; 1993, Ranathunga *et al.*, 2010*;* Soleimani and Ahmadi, 2014; Slaughter *et al.*, 1993). In general, the top package in the rear position had the greatest vibration level during truck transport.

2.5.4.2 Payload and vehicle size

There have been a limited published studies involving payload. Studies show that a loaded truck had lower g_{rms} and peak PSD values than an unloaded truck (Garcia-Romeu-Martinez *et al.*, 2008; Ranathunga *et al.*, 2010). For example, Garcia-Romeu-Martinez *et al.* (2008) investigated vibration levels of unloaded and loaded semi-trailers, including two types of suspension (the leaf spring and air ride suspensions). In the case of the air-ride suspension, the averages of g_{rms} for the loaded and unloaded semi-trailer were 0.089 *g* and 0.092 *g*, respectively. For the leaf spring suspension, the average of g_{rms} for the loaded truck (0.194 *g*) was also lower than for the unloaded truck (0.245 *g*). This research is in disagreement with that of Ranathunga *et al.* (2010), which showed a ten-fold increase in PSD value for the rear position with a loaded truck, compared to the front of the empty truck. In the case of fruit damage, Zeebroeck *et al.* (2008) found that light and half-loaded trucks gave with up to 33 times more bruised apples when compared with a fully loaded truck.

Furthermore, the larger size of truck had higher vibration levels than the smaller trucks (Jarimopas *et al.*, 2005; Chonhenchob *et al.* 2012). For example, 6-ton trucks had higher vibration levels than 2-ton trucks with the same suspension for tangerine shipments in Thailand (Jarimopas *et al.*, 2005).

Table 2.9: Frequency and g_{rms} levels in different locations in the vehicle and along the stack during road transport.

Vibration parameter	**Position in the vehicle**			**Country**	**References**
	Front	**Middle**	**Rear**		
Frequency (Hz)	10	15	14	Italy	Berardinelli *et al.* (2005)
	n/a	5	3.5	US	Hinsch *et al.* (1993)
g_{rms} (g)	4.22	5.59	9.03	Italy	Berardinelli *et al.* (2005)
	n/a	0.62	1.23	US	Hinsch *et al.* (1993)
	5.8-9.46	n/a	6.80-14.57	Iran	Soleimani and Ahmadi (2014)
	Position in the stack				
	Top	**Centre**	**Bottom**		
Frequency (Hz)	44-67	8-27	9-37	Italy	Berardinelli *et al.* (2005)
	21-22	21-22	27	Italy	Barchi *et al.* (2002)
g_{rms} (g)	7.65-16.78	7.55-16.68	6.97-12.75	Italy	Berardinelli *et al.* (2005)
	2.35	1.77	1.18	US	Hinsch *et al.* (1993)
	9.61	7.75	7.06	Iran	Soleimani and Ahmadi (2014)

n/a is not available data.

2.5.4.3 Vehicle suspension

There are commonly two main types of suspension: leaf spring and air ride suspensions (Figure 2.9). An air ride suspension gave a lower vibration level than a leaf spring type in studies (Garcia-Romeu-Martinez *et al.*, 2008; Hinsch *et al.*, 1993; Singh *et al.*, 2006; Timm *et al.*, 1996; Soleimani and Ahmadi, 2014; Zeebroeck *et al.*, 2008). In a fully loaded shipment in the US, for the higher PSD level, only the top 30% of recorded data was considered. The peak g_{rms} value of 30% high air ride values (0.50 *g*) was lower than that of 30% high leaf spring values (0.89 *g*) (Singh *et al.*, 2006).

The range of frequencies was slightly different for both suspension systems. The predominant frequencies of the air ride and leaf spring types during shipment in Spain were 1.5-2 Hz and 4-5 Hz, respectively (Garcia-Romeu-Martinez *et al.*, 2008). A similar result was obtained by Soleimani and Ahmadi (2014), who stated that the vibration of air ride suspension peaked at 3 Hz and that of leaf spring type peaked at 4 Hz during apple transport in Iran. However, the range of frequencies in both suspensions is different from the US shipment reported by Timm *et al.* (1996). The peak PSD of the air ride type was around 6 Hz, while the peak PSD of leaf spring suspension was approximately 4 Hz during truck transport. The peak PSD levels of the left and right sides of the vehicle were not different with air ride suspension at a similar frequency (4 and 20 Hz). In the air ride suspension, Hinsch *et al.*, (1993) stated that a frequency below 5 Hz related to less vibration damage during truck transport.

Figure 2.9: Suspension type of trailer. *Source*: Singh *et al.* (2006).

2.5.4.4 Speed and road surface condition

An increase of the acceleration level related to a higher speed and smoother road condition (Rissi *et al.*, 2008). An increase of speed affected g_{rms} level in both vertical and lateral directions (Lu *et al.*, 2010a). However, the result of Rissi *et al.* (2008) study in acceleration on a smooth road differs from the result of Lu *et al.* (2010a) research. Lu *et al.* (2010a) reported that a lower speed strongly correlated to g_{rms} and PSD values. At a lower speed on local roads, g_{rms} recorded data included shock and vibration values. Truck transport on a local road with speed (45-59.9 km/hr) had a higher g_{rms} value than on highways; however, an increase of speed over 70 km/hr on highways gave a higher g_{rms} value than a lower speed. These previous results are in agreement with Çakmak *et al.*'s (2010) research as shown in Table 2.10. The g_{rms} value of the unmetalled road at 3 Hz also was greater than the highway road at 15-17 Hz during transport in Turkey. Zeebroeck *et al.* (2008) suggested that the range of speed between 25 to 35 km/hr should be considered due to these speeds were expected a cause of apple bruising in bulk bins at 200 mm behind the rear axle.

The summarized data of truck transport on highway roads from four countries is in Table 2.10. The speed and vibration levels of truck transport were compared with Turkey and some European countries; the speed of the trucks on highway roads in Turkey, France and Italy was around 80 km/hr, except in Spain (over 100 km/hr). Whilst the speed of shipments on the unmetalled road was lower than on the highway by around 3 times (Barchi *et al.*, 2002, Çakmak *et al.*, 2010). In UK transport, goods vehicles are classified into two types such as < 7.5 tonnes and > 7.5 tonnes. The speed limit of goods vehicles (< 7.5 and > 7.5 tonnes) is 48 km/hr in built-up areas. The speed limits of trucks on highways (< 7.5 and > 7.5 tonnes) is 96 km/hr and 96-112 km/hr, respectively (The UK government, 2014). The peak PSD on highway roads was found at a frequency of 15-18 Hz in all four countries (Table 3.3). Lu *et al.* (2010a) also found that PSD level on highway roads was significantly higher than on a local road in Japan.

Table 2.10: The speed, frequency and g_{rms} of truck during shipments in Turkey, Spain, France and Italy.

Country/Highways	Speed (km/hr)	Frequency (Hz)	g_{rms} (g)	References
Turkey				
Highway	65-75	15-17	4.22-5.49	Çakmak *et al.* (2010)
Unmetalled	25-30	3	16.97-24.92	
Highways				
Spain	89-134	16-18	7.36-9.71	Barchi *et al.* (2002)
France	60-90	15-18	3.92-6.57	
Italy	70-80	16-17	5.79-7.59	

2.6 VIBRATION DAMAGE TO THE QUALITY OF FRESH PRODUCE

The vibration damage of fresh produce has been studied either by simulation in the laboratory or as an investigation in road transport. Several studies of vibration damage to fresh produce have been carried out using simulated transport. Soleimani and Ahmadi (2014) stated that there are four physical factors in fruit determination response to vibration levels, namely, intensity, frequency, direction and the duration. In this section 2.6, the factors of the simulated transport were mostly examined frequency (Hz), acceleration (g) and the duration (exposure time) (sec). Some road transport studies also investigated the effect of the position on the truck and stacking level on mechanical damage of fresh produce.

2.6.1 Simulated vibration to fresh produce damage

Simulation methods attempt to evaluate a packaging system that imitates the actual transport environment. The major equipment for physical simulation consists of a controller and a shaker (Sek, 1996). Additionally, the study of simulated truck transport in the laboratory was suggested to analyse separately shock and vibration by removing the shock value (Lu *et al.*, 2008). To separate shock and vibration levels, Lu *et al.* (2010c) also suggested that the acceleration criteria by removing shock level on the Japanese road were over 0.7 g. Mechanical damage to products depended on vibration and shocks in shipment environment and was also influenced by the temperature and humidity (Sek, 1996). During transport, vibration damage occurs through the constant vibrating motion of a vehicle over the road (Vigneault *et al.*, 2009).

Previous studies of mechanical damage caused by simulated vibration included apples (Vursavuş and Özgüven, 2004), pears (Acıcan *et al.*, 2007), peaches (Vergano *et al*, 1991), tomatoes (Sharan *et al.*, 2009; Bello *et al.*, 2013), figs (Çakmak *et al.*, 2010), kiwifruits (Tabatabaekoloor *et al.*, 2013), watermelons (Shahbazi *et al.*, 2010), fresh-cut cantaloupes (Saha *et al.*, 2009) and strawberries (Fischer *et al.*, 1992; Jiang *et al.*, 2001; Nakamura *et al.*, 2007b, 2008). The vibration conditions varied in frequency, acceleration and period of time to damage of fresh produce during truck transport are summarised in Table 2.11. The various frequencies or acceleration resulted in fruit damage. For instance, at the same level of acceleration (1 *g*), the frequency at 3.5 Hz or 18 Hz significantly caused more vibrated damage of pear than frequency at 9 Hz or 25 Hz. A frequency of 3.5 Hz should be concerned due to a difficulty to attenuate a low frequency (Slaughter *et al.*, 1993).

An increase of frequency, acceleration and time tests cause serious damage to fresh produce. Tabatabaekoloor *et al.* (2013) studied the effect of frequency level (7.5 and 13 Hz) and acceleration (0.3 and 0.7*g*) to kiwifruit damage. The highest damage to the fruits was found in vibration condition (13 Hz and 0.7 *g*) with a stack height of 340 mm. Also, a reduction of acceleration decreased Bartlett pear bruising was reported by Slaughter *et al.* (1993). At 9 Hz and 25 Hz, reducing the acceleration from 1 *g* to 0.67 g resulted in less bruise damage of pear. In the case of an increase of exposure time, Sharan *et al.* (2009) found that at a specific frequency (3 Hz), a threefold rise of vibrating time also increased to double the percentage of tomato damage.

Vibration damage may relate to the position on the floor, stacking or location inside the truck. For instance, 'Granny Smith' and 'Starkpur Golden Delicious' apples packed in a lower layer of wooden crates had a greater mechanical damage and vibration force than in an upper layer as reported by Acıcan *et al.* (2007). Watermelon in the top position of the bin had a higher damage level than in middle and bottom positions (Shahbazi *et al.*, 2010). These results agree with the findings of a tomato study, in which the level of tomato bruise increased from bottom to top in the traditional palm basket with cone shape (Bello *et al.*, 2013). However, pear damage was not consistent with the position on the floor or in the column of crates and was shown not to depend on the different acceleration levels (Berardinelli *et al.*, 2005).

The road characteristics may cause postharvest losses. In an investigation into the simulated transport of fig fruits, Çakmak *et al.* (2010) examined the simulated vibration tests under unmetalled road (3 Hz at 0.05 *g*) and highway road conditions (16 Hz at 0.25 *g*) for 1800 sec. A highway road condition gave a greater loss of fresh figs than with an unmetalled road condition. The fresh fig result differs from an apple study by Timm *et al.* (1999), in which highway transport with average speed of 105 km/h for 55 km was compared to the simulated vibration by ASTM standard D 4728-91 (method A). The result showed that the apple damage for both tests was a similar result.

2.6.2 Simulated vibration to strawberry quality

Strawberries are very susceptible to compression damage, followed by impact and vibration injuries (Figure 2.10) (Smith *et al.*, 2004; Ferreira *et al.*, 2008). In the case of strawberry damage, the most common frequency range for simulated vibration was 5 to 10 Hz (Table 2.11) (Fischer *et al.*, 1992; Jiang *et al.*, 2001; Nakamura *et al.*, 2007b; Nakamura *et al.*, 2008). The acceleration transmissibility and damage level of fruits had a high correlation value ($r^2 = 0.75$) (Nakamura *et al.*, 2008). Vibration level also directly affected strawberry damage. Fischer *et al.* (1992) reported that the frequency range of 5 to 10 Hz (0.6 *g*) for 600 sec caused the maximum damage to 'Selva' strawberries. Vibration level had no effect on colour and firmness and showed an unclear result in respiratory pattern.

During a vibration test, an increase of respiration rate in strawberries at 5°C and 15°C was approximately 40% and 17%, respectively. The vibration of strawberries affected firmness, but had no effect on TSS and TA contents (Tatara *et al.*, 1999). The previous results differ from Lui and Kojima (1997), who studied the effect of vibration level (0.5 *g*) for 3600 sec on respiration rate and quality strawberries. An increased storage temperature (0 to 20^{o}C for 3 days) directly affected a rise of respiration rate and a reduction of TSS content. Whilst Nakamura *et al.* (2007a) found that the vibration had no effect on the increase of bacteria after storage at 10^{o}C for 4 days. The findings of the previous studies suggest that vibration damage fruit should relate to the firmness and respiration rate of strawberries.

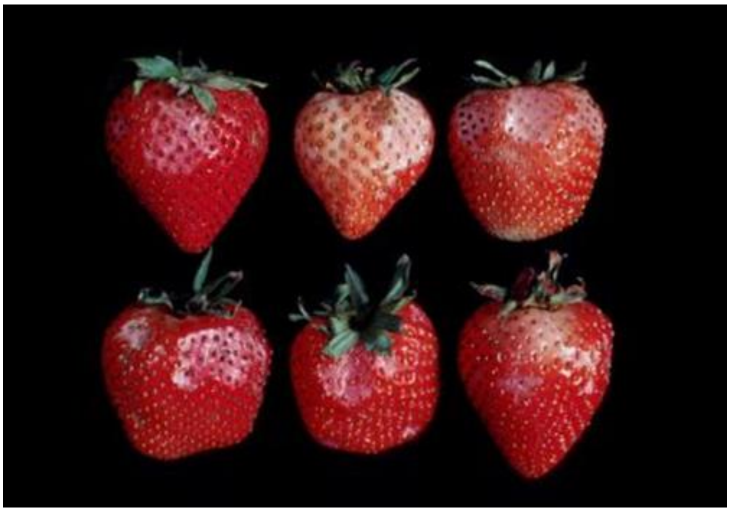

Figure 2.10: Vibration damage of strawberries. *Source*: Don (2015b).

2.6.3 Vibration from road transport to fresh produce damage

Over the past ten years, there have been some studies monitoring the quality of fresh produce during actual transport in Asia (Jarimopas *et al.*, 2005; Zhou *et al.*, 2007; Chonhenchob *et al.*, 2009; Ishikawa *et al.*, 2009). Most of the studies in the transport field have mainly focussed on the vibration levels, which were mentioned in section 2.5 (vibration during the actual transport).

The various frequency levels and damage in shipments depended on routes in each country. In Thailand, the maximum vibration levels occurred from farm to packing house, while the minimum levels occurred from distribution centres to retail stores. The lowest damage level of fresh produce was observed between distribution centres to retailers (Chonhenchob *et al.*, 2009). In a Japanese shipment, Ishikawa *et al.* (2009) found that there was usually no cherry damage during truck transport. The peak vibration frequency in truck transport was 15 Hz on the highway road from Yamgata to Narita airport. Another study in a strawberry shipment on a standard road was investigated by Kojima *et al.* (1999). All frequencies (3.35, 7 and 13.5 Hz) with acceleration (0.02-0.18 *g*) caused strawberry damage during transport, even when the peak of vertical acceleration was at 3.35 Hz.

The frequency during the truck transport in Turkey matches that of the Japanese shipment. The peak range of PSD on highway road was 15-17 Hz at the range of g_{rms} (0.18-0.25) during fig transport from orchard to market. A visually attribute assessment of the highway shipment also showed a greater increase of the fig damage than the unmetalled road condition due to the longer transport time (Çakmak *et al.*, 2010). A similar agreement was reported by Soleimani and Ahmadi (2014). Even though highway conditions have a smoother surface than unmetalled road conditions, the most severe damage of fruits was found in highway road because of transport time. However, these results differ from Timm *et al.* (1996), who found that apple bruising was not significantly influenced by trip distance and suspension type during shipment in the US.

The highest damage of fresh produce during road transport still occurred at the top level, which is the same as in the simulated vibration test. In a strawberry shipment in Iran, a higher position of the bin along stacking increased mechanical damage. The bottom row within the box had the highest strawberry damage as compared to the middle and upper rows (Aliasgarian *et al.*, 2013). During transport in Thailand, the highest damage of tangerines was also at the top basket for truck payload capacity (2-tonne and 6-tonne trucks) and shipment speed (20 to 80 km/hr) (Jarimopas *et al.*, 2005). Furthermore, 'Huanghua' pears in the top RPCs of stacking in the rear position had the highest mechanical damage to pear surface, followed by in the front-top RPCs and in the front and rear of bottom RPCs (Zhou *et al.*, 2007). This pear damage is similar to that of apple damage (Soleimani and Ahmadi, 2014); the apple vibration levels at the top RPCs of the column were significantly higher than the fruits at the bottom RPCs of the column.

Table 2.11: The condition used for the simulated vibration to damage of fresh produce during road transport.

Commodity	Frequency (Hz)	Acceleration (*g*)	Time (sec)	References
Apples	8 to 9	0.63	1,200	Vursavuş and Özgüven (2004)
	4.17	n/a	600	Acıcan *et al.* (2007)
Pear	5 to 200	0.4	300	Berardinelli *et al.* (2005)
Peach	6	0.94	300	Vergano *et al.* (1991)
Tomatoes	3	n/a	3,600	Sharan *et al.* (2009)
	24	n/a	n/a	Bello *et al.* (2013)
Figs	16	0.25	1,800	Çakmak *et al.* (2010)
Kiwifruit	13	0.7	n/a	Tabatabaekoloor *et al.* (2013)
Watermelons	7.5	0.7	3,600	Shahbazi *et al.* (2010)
Strawberries	5-10	0.6	600	Fischer *et al.* (1992)
	5	1.6	40	Jiang *et al.* (2001)
	7	1	3,600	Nakamura *et al.* (2007b)
	7 to 35	0.6	n/a	Nakamura *et al.* (2008)

n/a is not available.

2.7 TEMPERATURE MANAGEMENT DURING LAND REFRIGERATED TRANSPORT OF FRESH PRODUCE

Perishable products are delivered from the location of food production to the consumer using various modes of transportation (Thompson, 2002a). Temperature management by using refrigeration technologies is an important factor to maintain the quality of fresh produce in the supply chain (Vigneault, 2005). The appropriate control and management of temperature is important for the fresh produce delivered to consumers and so that fresh produce is kept in a good condition for food safety (Aung and Chang, 2014). The cold chain use requires a specific temperature in each type of fresh produce as well as a loading vehicle for mixed loads (the different fresh produces or food products in the same load) (LeBlanc and Hui, 2005).

On the North American highways, the refrigerated semi-trailers and trucks are normally used in delivery of perishable products, even if the refrigerated road transportation is not commonly used around the world (Vigneault, 2005). In developing countries, semi-trailers may be a smaller size to operate on unimproved roads. Truck transportation is much less energy efficient as compared to rail transportation (Morris, 2011). In terms of energy consumption in the UK, the road transport sector has accounted for 74% of total transport energy consumption when compared with an air transport sector (23%) (Department of Energy and Climate Change, 2015). A 2010 report showed that a vehicle size of over 3.5 tonnes is used for widely around 30% of the total CO_2 emission from the British food transport (Department for Environment Food and Rural Affairs, 2012).

2.7.1 Temperature of transport and transport of mixed load

Most factors affecting perishable products during transport are external factors such as temperature, transport of mixed loads, physical injury, humidity, moisture loss, and gas composition. Two major factors in this section are reviewed in temperature during road transport and transport of mixed load. However, the information of physical injury is explained in the impact and vibration injuries which are mentioned in the section 2.4 (impact damage to fresh produce) and in the section 2.6 (vibration damage to the quality of fresh produce). Furthermore, the effect of temperature on the quality of fresh produce also is reported in the next section 2.8 (strawberry storage).

2.7.1.1 Temperature of fresh produce during transport

The principal practice of postharvest handling of perishable products is to maintain cool chain management as long as possible. The cool chain of perishable products should hold at their lowest recommended temperature at each point handling (Vigneault *et al.*, 2009). The recommended storage and transport temperature of horticultural produce are mainly categorized into four groups, namely 0 to 2^{o}C, 4 to 7^{o}C, 7 to 10^{o}C and 13 to 18^{o}C (Thompson, 2002a). Surveys of strawberry temperature during truck transport were reported (Macnish *et al.*, 2012; Russell *et al*., 2009). Macnish *et al.* (2012) investigated the temperature during 'Albion' strawberry shipment from California to Jacksonville (Florida) or Atlanta (Georgia). The range of temperature in a long period of shipment varied from 0 to 3.8^{o}C from six shipments. In the case of a short period for delivery with fluctuating temperature, Russell *et al*. (2009) monitored the temperature of strawberries during transport from storage to retail stores over 2 years. During transport to the wholesale storage, the temperature of strawberries dropped to 3-5^{o}C, then increased to 7-15^{o}C during delivery to the retail stores. Veneault *et al*., (2009) reported that the transit period from local distribution centres to markets are often less than 8 hours.

2.7.1.2 Transport of mixed load

The retail and food service of logistic delivery try to handle a wide range of perishable and non-perishable products in the same semi-trailer on a daily basis or three to four times per week. The recommended storage temperature of mixed load for delivery should be controlled between wholesalers and customers with various transport options, multi-compartment trucks and mini-containers or insulating covers (LeBlanc and Hui, 2005). The other considerations of horticultural produce delivery are the recommended relative humidity, the sensitivity and production of gases and volatiles, and the absorption and production of odour (Veneault *et al.*, 2003). In temperature delivery of other food products, the desired temperature in transit (except fresh meat and seafood products), butter and cheeses are around 1 to 4^{o}C and shell eggs are 4 to 7^{o}C (Ashby, 2008).

2.7.2 Refrigeration and mechanical refrigeration

The function of refrigeration is the removal of excess heat and providing temperature control for food products in vehicle (Ashby, 2008). Three main sources of heat temperature for transport are firstly the initial remaining heat within trailer and field heat before loading, secondly the penetrating external heat load during transport and thirdly the internal heat from produce respiration (Hui, 2001). Most mechanical refrigeration units on semi-trailer are typically nosemounted, including engine, condenser, the evaporator and air fans inside the trailer (Ashby, 2008). Currently, many innovative refrigeration units equip microprocessor controllers to monitor refrigeration operation and signal the driver in case of malfunctions (Thompson, 2002b). Moreover, the real time asset management system shows only a track temperature but does not determine a certain temperature of produce (Ben-Tzur and Ward, 2010).

2.7.3 Air circulation

Air circulation systems must be considered to remove rapid vital heat from the product which can penetrate the walls, floors and ceiling inside the trailer to refrigeration unit (Ashby, 2008). The flow rate of the first circulation in the front part of the semi-trailer was higher around ten times than the second recirculation in the rear position (LeBlanc and Hui, 2005). Air circulation system in refrigerated trailers can be divided into two major systems such as a top-air delivery and a bottom-air delivery.

A top-air delivery or overhead system is widely used in refrigerated semi-trailers (Figure 2.11), whereas a common bottom-air delivery system is used in marine and intermodal containers (Figure 2.12). The pattern of air circulation in refrigerated semi-trailers are illustrated in Figure 2.11. The refrigeration unit of a top-air delivery starts to blow cold air with high velocity air from the front to the rear of the trailer above the product load. Along air circulation above loading pallet to the rear door, some cool air moves to the floor along the side wall of the trailer. The air flows from the rear door underneath the pallet along the floor, then returning and flowing up to the evaporator (Vigneault *et al.*, 2009).

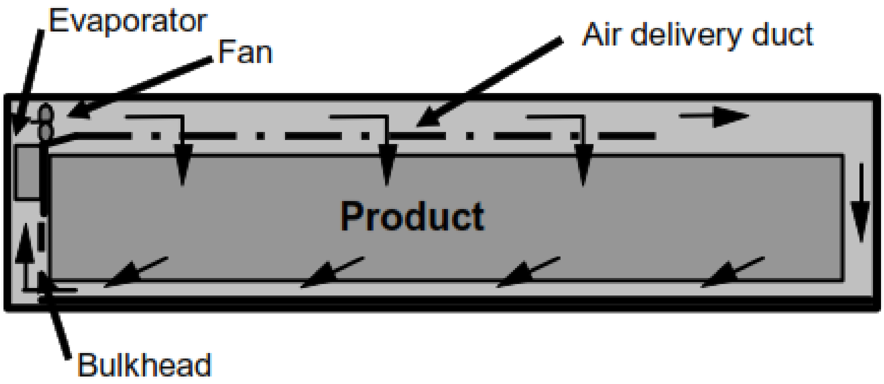

Figure 2.11: Air flow pattern in a top-air delivery system. *Source*: Vigneault *et al*. (2009).

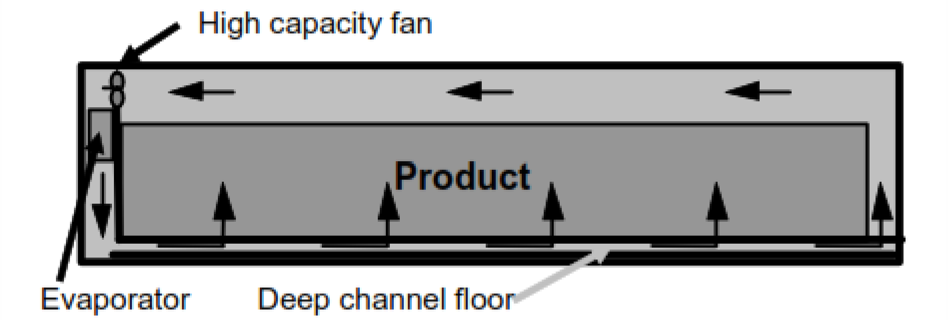

Figure 2.12: Air flow pattern in a bottom-air delivery system (normally only in marine container). *Source*: Vigneault *et al*. (2009).

A top-air delivery system often gives the uniformity of cool temperature in semi-trailers during road transport. Most uniformity of air distribution studies was reported in the area from front to rear location and along a stack (Hui *et al.*, 2006; Havey *et al.*, 1980; Rediers *et al.*, 2009; Pelletier *et al.*, 2011). The temperature was stable after door closing within 60 minutes. The lower airflow areas were found in the middle section across the width and along the length, and the middle and bottom section across stacking height (Hui *et al.*, 2006).

In the studies of strawberry shipment, the temperature of the centreline load had a lesser variation and was cooler than the load against the side wall in a truck shipment of California strawberries (Havey *et al.*, 1980). Thompson *et al.* (2002b) also supported that the air and pulp temperatures of strawberries for side wall loading were higher than the centre-loaded section around 1.1 to

1.7°C. Recently, Pelletier *et al.* (2011) monitored temperature in different locations in a semi-trailer during strawberry shipment from California to Florida as a setting point temperature at 1.1°C. There were 24 pallets for the full loading and 18 layers in each stack (pallet). As shown in Table 2.12, overall, the pulp temperature of the bottom level was higher than the top and centre positions which may be affected by the radiant heat from the road surface. The lowest temperature of the whole load was located in the pallets at the front (T1) and rear (T23) positions of the trailer where should be placed the fruits to maintain excellent strawberry quality.

Table 2.12: The change of pulp temperature in 'San Juan' strawberries at the bottom, centre and top level of pallet in different locations inside transport trailer (Pelletier *et al*., 2011).

Pallet	**Temperature (°C)**		
	Bottom	**Centre**	**Top**
T1 (Left-Front)	1.7	3.0	2.8
T11 (Left-Middle)	5.8	3.7	2.6
T23 (Left-Rear)	2.1	2.6	2.6
T11 (Left-Middle)	5.8	3.7	2.6
T12 (Right-Middle)	4.2	2.4	3.9
T15 (Left-Middle)	5.1	5.5	4.3
T16 (Right-Middle)	n/a	4.2	3.4

n/a is not available data.

2.7.4 Pallet type and size for fresh produce

Pallets play an important role in unitizing shipping containers, distribution and protection products. There are various types of pallet material such as wood (a primary pallet), plastic paper and metal. The globally standardized pallet sizes have not been established for global distribution. As shown in Table 2.13, pallet sizes generally used across the globe, namely North American pallets, Euro pallets, Asian pallets and ISO pallets. The specification of ISO 6780:2003 is described as the principal dimensions and tolerances of all entry types and materials (Chonhenchob *et al*., 2011).

Table 2.13: Pallet sizes generally used across the globe (Chonhenchob *et al*., 2011).

Pallet type	Size (mm x mm) or (in x in)
North American pallets	48 in x 40 in (1200 mm x 1000 mm)
Euro pallets	EURO (800 mm x 1200 mm)
	EURO 1 (1200 mm x 1000 mm)
	EURO 3 (1000 mm x 1200 mm)
	EURO 6 (800 mm x 600 mm)
Asian pallets	1100 mm x 1100 mm and 800 mm x 1200 mm

2.7.5 Packaging system for fresh produce

A food packaging system relates to four levels of packaging. The primary packaging is usually an individual unit at retail stores (Lee *et al*., 2008) such as the plastic bag, punnet, clamshell, net bag, plastic tray. In the UK, a primary packaging of strawberries is generally used as a polyethylene terapthalate (PET) or rPET (recycled PET) with either a clip-on lid or a heat seal film with a small piece of bubble sheet (Terry *et al.*, 2011). The secondary package contains a number of primary packages (Lee *et al.*, 2008). For instance, a corrugated fibreboard and reusable plastic container are usually used in the transportation and distribution of strawberries in the UK (Terry *et al.*, 2011). The tertiary and quaternary packages are typically a stretched-wrapped pallet and a large metal container, respectively (Villahermosa *et al.*, 2011).

2.7.5.1 Clamshell or punnet (vent size and position) and Modified Atmosphere Packaging (MAP) of strawberries

Clamshell and punnet packages are commonly used for fresh strawberries. Boyette *et al.* (2013) reported that clamshells have been popular because of inexpensive cost, versatility and good protection. Thompson and Knutson (1997) suggested that the clamshell packages with 7% and 13% vent were the optimum vent area for the forced-air cooling of strawberries. The large top and bottom vent area (without both side and end vent areas) cooled slower than other clamshells with side and end vent. Anderson *et al.* (2004) stated that the percentage of vents on the trays did not certainly relate to the cooling rate. The clamshell package and tray should be designed together to improve cooling efficiency. Moreover, the package configuration related to the pulp temperature of strawberries. Mirzaee and Bishop (2010) reported that the punnet of strawberry by stacking inside plastic crates gave a lower temperature change than side by side configuration. The better air ventilation can reduce the strawberry damage caused by condensation to prevent postharvest disease during supply chain. Furthermore, a commercial strawberry punnet from one supplier in the UK was also placed on a red non-woven sheet at bottom of the strawberry pallet instead of a general bubble sheet. The main properties of the red non-woven sheet may affect a reduced fruit bruise, absorbed moisture inside MAP or fruit leakage from bruised fruit. However, Mirzaee and Bishop (2010) found that the plastic sheet in a punnet on net shelf gave the lowest disease of strawberries when compared with net and tissue pads. Therefore, the material sheet in punnets may reduce bruising damage as a cushion property and disease level.

Modified atmosphere packaging (MAP) is mainly divided into passive MAP and active MAP. Passive MA can be achieved by the natural interplay between the respiration of fresh produce and transfer of gas through film permeability characteristics (Zagory and Kader, 1988). Active MAP can be achieved by flushing out the air within the package with the desired gas mixture. The other techniques are the uses of some gas absorbers (O_2, CO_2, or C_2H_4) or vapour absorbers and antimicrobial agents (Zagory and Kader, 1988; Gontard and Guilaume, 2010). The recommended O_2 and CO_2 of Controlled atmosphere (CA) and MAP conditions for strawberries are 5-10%O_2 and 15-20%CO_2. Their tolerance levels of low O_2 and high CO_2 concentration are 2%O_2 and 15%CO_2 (Kader *et al*., 1998). In the US, for long distance transport, strawberries are flushed by elevated CO_2 (12 to 15%CO_2) to reduce the spread and development of decay by MAP condition, especially Botrytis rot. The CO_2 treatment uses a completely enclosed pallet load of the cooled strawberries in a sealed plastic bag (Mitcham and Mitchell, 2002). In the UK, the commercial fresh strawberries are commonly packed in vented punnets or clamshells; therefore MAP is rarely used in commercial packing and mainly done only in the research area (Terry *et al*., 2009).

2.7.5.2 Corrugated fibreboard of fresh produce

The three most generally styles of corrugated boxes for fresh produce are slotted boxes, telescoping boxes and rigid/bliss boxes. Corrugated common footprints (CCFs) were presented in 2000 and have been developed in the United States by the Fibreboard Box Association and the European Federation of Corrugated Board Manufacturers (FEFCO) (Figure 2.13) (Singh *et al.*, 2009). The B flute for double wall configuration is usually used in horticultural crops (Thompson and Mitchell, 2002; Boyette *et al.*, 1996). The most corrugated fibreboard container should have around 5-6% vent area without a reduction of a stacking strength. The vent opening on tray is used widely for berries and should have up to 15% vent area with a few large holes instead of many small holes for speeding the cooling rate (Thompson *et al.*, 1998). In the vent position on the tray, vents across the top of the tray provided rapidly the cooling of blueberries. Venting at the bottom of corrugated fibreboard trays does not develop cooling rates of blueberries; these vents may affect the improvement of air circulation and maintain temperature during storage (Leyte and Forney, 1999). In case of payload and damage protection, CCFs had a greater payload of berries about 11% and significant a lesser bruising with the same cooling rate than reusable plastic crates (RPCs). The packed table grapes in CCFs allowed 6% larger payload with no difference in weight loss and cooling rate (Corrugated Packaging Alliance, 2003).

Figure 2.13: A corrugated common footprint (CCF). *Source*: Singh and Singh (2007).

2.7.5.3 Plastic crates and reusable plastic crates (RPCs) of fresh produce

The key advantages of plastic crates are resistant to water and moisture and can be clean and sanitized before packing fresh produce (Chonhenchob *et al.*, 2011). In the United States and

European for the distribution of fresh produce, reusable/returnable plastic containers are significantly increased use for bulk packaging because RPCs are durable and high-quality containers and have good pooling systems for supply chain management (Vigneault *et al.*, 2009; Chonhenchob *et al.*, 2011). A key role of RPCs is an environmentally friendly package due to 39% less total energy, 95% less total solid waste and 29% less total greenhouse emission (Franklin Associates, 2004).

2.8 STRAWBERRY STORAGE

The marketing of perishable fresh products frequently needs some kind of storage system to control temperature fluctuations from harvesting through sales. The important aims of storage are firstly to slow the biological activity of these products, secondly to retard the growth and spread of microorganisms, thirdly to decrease water loss, which causes wilting and shriveling, and finally to decrease and avoid ethylene gas for product susceptibility (Thompson, 2002a). The optimum temperature of strawberry storage is recommended at 0^{o}C with 90 to 95% relative humidity (RH) to provide a storage life up of to 7 days (Mitcham, 2014), but the transportation to market is the longest period of total postharvest life in fresh strawberries (Mitcham and Michell, 2002). However, the temperature changes of strawberries during transportation are described in the section 2.7 (Temperature management during land refrigerated transport of fresh produce). In the current section, therefore, the consideration of temperature changes focuses firstly on the effect of cooling on the strawberry quality after storage and secondly on the effect of temperature on retail display and simulated storage on strawberry quality changes.

2.8.1 Cooling of strawberries

Temperature management of horticultural products commonly begins at harvest and field handling, and then produce heat from the field and respiratory metabolism is removed rapidly by cooling before shipment and storage (Thompson, 2014; Will *et al.*, 2007). Forced-air cooling is the only successful cooling method for strawberries in commercial handling. Since strawberries easily lose moisture and are not tolerant of high moisture due to disease and injury problems, neither hydrocooling, package-icing nor vacuum cooling are practiced. Room cooling is not suitable for strawberries because of the slower cooling rate (Thompson *et al.*, 2002c). The time to cool strawberries by room cooling to 0^{o}C was 18 hours (Atta-Aly *et al.*, 1999), while the time for forced-air cooling was only 2 hours to 1^{o}C from the initial flesh temperature at 24^{o}C (California Strawberry Commission, 2006). A short delay of about 0 to 8 hours from forced-air cooling directly affects the quality characteristics of berries after storage. Delay for cooling of only 1 hour following storage is insufficient to control strawberry decay (Nunes *et al.*, 2005b). Nunes *et al.* (1995) showed that a 6-hour delay in cooling in 'Sweet Charlie' strawberries at 30^{o}C caused lower firmness, ascorbic acid, sugar content (fructose, glucose and sucrose) and darker red colour as compared to no delay in cooling.

2.8.2 Air temperature at retail display

In recent years, researchers have shown an increased interest in monitoring temperature of fresh produce supply chain. A temperature survey in a commercial strawberry handling in Canada was conducted by Russell *et al.* (2009). The temperature storage at wholesale was 3-4^{o}C, and then increased to 15^{o}C during delivery to the retail stores. The strawberry temperature at retail stores was maintained at approximately 5-10^{o}C. In another study in the US, the temperatures at retail displays from three retail stores (12 refrigerated and 15 non-refrigerated displays) were investigated. The average air temperature inside the three retail stores and pulp temperature were about 7^{o}C and 5.7^{o}C, respectively. The maximum shelf-life of strawberries was only 2 days for visual quality evaluation at 3.8 scores (3.0 = acceptable for sale) (Nunes *et al.*, 2009). In the UK study, Chaiwong and Bishop (2015) investigated the temperatures of air and strawberry pulp from 11 supermarket stores, which was 17.2 and 6.3-13.0^{o}C, respectively. In the previous survey studies, therefore, the temperature in the supply chain of strawberries (3-17^{o}C) is higher than the recommended storage temperature (0^{o}C) (Mitcham and Michell, 2002; Russell *et al.*, 2009; Nunes *et al.*, 2009; Chaiwong and Bishop, 2015).

2.8.3 The changes of colour, water loss, anthocyanins and phenolics

The strawberry surface colour turns to a darker or deep red and may relate to anthocyanin concentration during low storage temperature (Sacks and Shaw, 1993; Hananz *et al.*, 2008; Holcroft and Kader, 1999). For example, the low temperature storage ($0^{o}C$) affected a reduction in L* (lightness) and C* (chroma) values of strawberry surfaces, but influenced an increase C* value of its pulp. The different C* results between surface and pulp may vary for different pigment concentrations (anthocyanins and phenolic compounds) (Sacks and Shaw, 1993). However, the L* and h* values of 'Osogrande' strawberries increased after storage at $5^{o}C$ and $15^{o}C$, while the reverse results in 'Camino Real' was observed in a reduction of L* and h* values throughout at both temperatures (Pineli *et al.*, 2012). Anthocyanin compounds (pelargonidin 3-rutinoside and pelargonidin 3-glucoside) were also highly correlated to a* value of strawberry surface and L* value of the pulp, respectively (Hananz *et al.*, 2008). From the studies mentioned above, the colour attributes and anthocaynin compounds of strawberries depend on strawberry cultivar and fruit surface or pulp. Moreover, the strawberry storage at low temperature did not suppress anthocyanin synthesis (Holcroft and Kader, 1999). The lowest anthocyanin content was observed in the deep red colour after storage for 8 days, which correlated to the highest pH level (Kalt *et al.*, 1993).

A higher temperature and time for storage also induced the accumulation of anthocyanin concentrations (Kalt *et al.*, 1993, 1999; Cordenunsi *et al.*, 2005) as well as total phenolic contents (Pineli *et al.*, 2012). During strawberry transportation from harvesting to retail display, total anthocyanins from the fluctuating temperature, around $20^{o}C$ for 9 hours, were higher than the semi-constant condition at $3^{o}C$ (Nunes *et al.*, 2003). In contrast to the previous finding, pelargonidin 3-glucoside content (88.1% of total anthocyanins) significantly declined after storage at a higher temperature (20 and $30^{o}C$) for 5 days (Kalt *et al.*, 1993). In the change of polyphenol level at $5\text{-}15^{o}C$, an increase of total phenolic contents was observed at around 64-79% during storage for 4-6 days (Pineli *et al.*, 2012). While at a lower temperature storage at $0^{o}C$, total phenolic level of strawberries was kept at a constant level (Ayala-Zavala *et al.*, 2004; Cordenunsi *et al.*, 2005).

The maximum weight loss was considered as 6% for a limited sale of strawberries (Robinson *et al.*, 1975). For truck transport in the US, the weight loss of packed strawberry clamshells was 0.5 to 4.4% during the transport from harvest to a distribution centre in Florida (Pelletier *et al.*, 2011). In another study in a refrigerated truck transport from Watsonville (California) to Jacksonville (Florida) or Atlanta (Georgia), the weight loss of strawberries was at the low level of 0.8% during 2.5-5 days at 0-3.8^{o}C (Macnish *et al*., 2012). In laboratory research, several studies investigating different temperature have been carried out on weight loss during storage. For instance, strawberry storage at 5^{o}C (5%) had a lower percentage of weight loss than at 15^{o}C (8%) for 8 days (Pineli *et al.*, 2012). Similarly, Kalt *et al.* (1993) found that the highest weight loss of the full red stage at 5^{o}C and 10^{o}C (4.89%) was lower than that of 20^{o}C or 30^{o}C (13.88%) under the light conditions. Water loss affected a reduction of anthocyanin and phenolic contents (Nunes *et al.*, 2005; Ayala-Zavala *et al.*, 2004; Shin *et al.*, 2007). The anthocyanin contents of strawberries reduced during the first 5 days at 0 to 5^{o}C (Ayala-Zavala *et al.*, 2004). A greater water loss in 'Oso Grande' strawberries (11%) related to the lower anthocyanin level and other soluble phenolic content after storage at 1^{o}C for 8 days (Nunes *et al.*, 2005a).

High relative humidity conditions also reduced weight loss of strawberry storage. For example, Shin *et al.* (2007) found that weight loss of strawberries at 85% to 95% RH (0.4 to 0.6%) had a lower weight loss than 75% RH (0.8%) during storage at 0.5 to 10^{o}C for 4 days. Similarly, Shin *et al.* (2008) found that 65% RH condition still had a higher weight loss than 95% RH, particularly for the white tip maturity stage. Moreover, Shin *et al.* (2007) also stated that the lowest weight loss also related to a maximum phenolic content, while the accumulation of anthocyanin in strawberries was not affected by any RH conditions. In the case of packaging, which minimizes air movement, packed strawberries in dome lids (four 0.5 cm diameter ventilation holes) provided a higher weight loss of around 3% when compared to polyethylene (PE) wrapping (1.35%) during storage at 5^{o}C for 15 days (Collins and Perkins-Veazie, 1993).

2.8.4 Changes of firmness

Storage at a higher temperature or a fluctuating temperature affects strawberry firmness (Collins and Perkins-Veazie, 1993; Nunes *et al.*, 2003; Shin *et al.*, 2007, 2008). However, strawberry firmness was not affected by RH conditions from 65 to 95% RH (Shin *et al.*, 2007, 2008). During handling and retail display, strawberries exposed to warm conditions at 25^{o}C for 8 hours had higher softening and less attractive appearance than a continuous temperature at 1^{o}C. However, the shelf-life of both conditions was not different (Collins and Perkins-Veazie, 1993). This study is in agreement with the findings of Nunes *et al.* (2003) which showed strawberries from a fluctuating temperature induced more fruit softening and unacceptable fruit for sale. Vicente *et al.* (2002) found that the application of heat treatment at 45^{o}C for 3 hours could maintain the texture of fruit at 1^{o}C for 7 days. There was no firmness difference between the heated fruit and control after 14 days. In case of the low storage temperature, Nunes *et al.*, (2006) reported that storage of strawberries at 1^{o}C for 8 days did not affect firmness changes, although the fruit appeared to be more ripening. However, Shin *et al.* (2007) found that strawberry firmness increased during storage at both 0.5 and 10^{o}C for 2 days.

2.8.5 Changes of sugar and acid

There are three possible carbon resources for soluble sugar synthesis after harvesting: starch, organic acids and cell wall degradation. It may be that cell wall degradation plays an important factor in sugar accumulation due to a reduction of fruit firmness and the increase of TSS and xylose contents (Cordenunsi *et al.*, 2003). A number of studies have found that TSS content decreased during cold storage (0 to 5^{o}C), whereas an increase of temperature (10 to 20^{o}C) induced a reduction of TSS content (Ayala-Zavala *et al.*, 2004; Cordenunsi *et al.*, 2005; Pineli *et al.*, 2012; Shin *et al.*, 2007). The sugar reduction in strawberries may be due to high respiration after storage at 15^{o}C (Pineli *et al.*, 2012). For instance, the respiration rate of strawberries increases rapidly, around 5 fold, from 0^{o}C (12-20 mg CO_2/kg.hr) to 10^{o}C (50-100 mg CO_2/kg.hr) (Mitcham, 2014). Pineli *et al.*'s (2012) result supports Cordenunsi *et al.* (2003) and found that the sucrose contents of 5 strawberry cultivars declined rapidly within 2 days after storage at 6^{o}C, whereas glucose and fructose contents increased gradually during storage conditions. In contrast, the reduction of sugar content differs from the study of Collins and Perkins-Veazie (1993) where TSS level did not change significantly under any simulated retail display conditions. Jeong *et al.* (2011) also found that TSS content of strawberries was little changed during both storage at 0^{o}C and simulated display at10^{o}C.

Storage at cool temperature and high RH condition had no effect on changing citric acid or TA content (Cordenunsi *et al.*, 2003; Collins and Perkins-Veazie, 1993; Shin *et al.*, 2007; Ali *et al.*, 2011). In contrast, the TA content of strawberries increased after transferring to 20^{o}C for 4 days (Vicenta *et al.*, 2002). At the different maturity stages, the TA contents of one-half-coloured and three-quarter-coloured fruits also increased during storage at 1^{o}C for 8 days, except a reduction in the full red stage (Nunes *et al*., 2006).

2.8.6 Changes of ascorbic acid

Vitamin C (ascorbic acid: AA) is more sensitive to a storage for a long period, high temperature, low relative humidity (Mitcham, 2007). AA content also decreased by around 38% at 0^{o}C (10 days) and 50% at 6^{o}C (6 days) after storage (Cordenunsi *et al.*, 2003; Koyuncu and Dilmaçünal, 2010). In contrast, AA levels of 'Kent' strawberries had little change during storage temperature from 0 to 30^{o}C (Kalt *et al.*, 1999). In a commercial supply with fluctuating temperatures, AA concentration of fresh strawberries decreased by around 9% from harvest to wholesale, and 3% from wholesale to retail, but was no a correlation with water loss (Russell *et al.*, 2009). However, the relationship between weight loss and AA changes was not clear during strawberry storage. Nunes *et al.* (1998) found that a strong relationship between weight loss and total AA was highly significant (r = 0.87 to 0.99), especially for storage at 20^{o}C. In contrast, Shin *et al.* (2007)

reported that AA content of strawberries was not affected when stored at 3^{o}C (65 or 95% RH) or 10^{o}C (65 or 95% RH) for 12 days.

2.8.7 Decay incidence during storage

To control decay, storage and temperature management at the lowest safe temperature is the simplest method to prevent deterioration of the fruit. The growth of grey mould can be delayed at 0^{o}C, whereas Rhizopus rot or leak disease can be totally suppressed by temperatures lower than 5^{o}C (Mitcham, 2014). At a temperature of 0.5^{o}C with any RH condition, there was no effect on decay incidence of ‘Jewel’ strawberries, while with higher temperature and higher RH conditions, an increase of decay was induced (Shin *et al*., 2007). At a higher temperature, the decay incidence of ‘Osograde’strawberries at 15^{o}C rapidly reached about 90% as compared to 32% at 5^{o}C within the first 4 days (Pineli *et al.*, 2012). In the simulated transport of strawberries from harvesting to retail display, the fluctuating temperature activated a higher decay incidence (bruised and inoculated (*Botrytis cinerea*) berries) than semi-constant temperature (Nunes *et al.*, 2003). Similarly, fluctuating temperature showed Botrytis infection (42.3%) at around twice as high as constant temperature (24.3%) (Mirzaee *et al.*, 2008). Additionally, with the actual transport of strawberries for 4 days and then simulated retail display, the initial observation showed grey mould after only a day at 21^{o}C, particularly in the bruised area. After 2 days, the bruised areas showed mycelium growth and soaked brownish depressions (Pelletier *et al.*, 2011).

CHAPTER 3

GENERAL MATERIALS AND METHODS

3.1 INTRODUCTION

This chapter describes the preparation of plant materials for the impact and vibration tests. The fruit samples were tested by impact and vibration tests and then checked the fruit quality in the initial day (day 0) and the end of the storage at 10±1^{o}C and relative humidity (RH) at 70±5% RH. The quality determination of strawberries also explains the physical and chemical properties, including the quality category and severity score by visual assessment. However, the impact and vibration treatments are described in a particular experiment in Chapter 4 and Chapter 5, respectively.

3.2 PLANT MATERIALS

Strawberry plants cv. 'Elsanta' and 'Sonata' with A+ grade and crown diameter ≥ 15 mm were provided by RW Walpole Ltd, UK. The strawberry plants (10 plants in each bag) were grown in a peat bag with a size of 1000 mm (Sinclair, UK) using soil less system on a wood bench called 'table top growing' (Figure 3.2A). A total of 400 plants of each cultivar also were grown in the greenhouse at Writtle College, Chelmsford. There were three cultivations for using in impact and vibration tests. The winter cultivations through to harvesting in 2014 and 2015 were conducted two periods from 10th February to 27th May (the 1st winter cultivation) in 2014 (Figures 3.1A1-A2) and from 10th February to 17th May (the 2nd winter cultivation) in 2015 (Figure 3.1B). The summer cultivation was conducted from 26th June to 24th August in 2014 (Figure 3.2). The automatic fertigation system by a single drip line was used in the greenhouse (Figures 3.1 and 3.2). The schedule of strawberry planting during the winter and summer cultivations is presented in Table 3.1. Two main types of water soluble fertilizer such as 18-10-18 + 2.5MgO + TE and 10-10-30 + 3.3 MgO + TE (Evereis, the Netherlands) were used. After strawberry planting, the fertigation by a drip irrigation started after approximately 6 weeks for the winter cultivation and a week for the summer cultivation.

Table 3.1: The timetable of fertigation by a single drip line for the greenhouse production at Writtle College during the winter cultivation in 2014 and 2015 and the summer cultivation in 2014.

Week	Activity
Winter cultivation (February-May) 2014 and 2015	
2^{nd} week in February	Hand watering after planting strawberries (Elsanta and Sonata cultivars)
2^{nd} week in March	Started watering of drip irrigation system at the rate of 133 ml/min for 4 min per a day
3^{rd} week in March	Removed fleece cover and fertigation (18-11-18 + 2.5 MgO) for 4 min per a day
1^{st} week in April	Fertigation (18-11-18 + 2.5 MgO) for 5 min per a day (twice a day)
2^{nd} week in April	Fertigation (10-10-30 + 3.3 MgO) for 5 min per a day (twice a day)
3^{rd} week in April	Fertigation (10-10-30 + 3.3 MgO) for 5 min per a day (3 times a day)
1^{st} week in May	Started fruit harvesting with fertigation (10-10-30 + 3.3 MgO) for 5 min per a day (3 times a day)
Summer cultivation (June-August) 2014	
4^{th} week-June	Hand watering after planting strawberries (Elsanta and Sonata cultivars)
1^{st} week-July	Removed fleece cover and start watering of drip irrigation system at the rate of 133 ml/min for 4 min per a day and sometimes twice a day
3^{rd} week July	Fertigation (18-11-18 + 2.5 MgO) for 5 min per a day (3 times a day)
4^{th} week July	Fertigation (10-10-30 + 3.3 MgO) for 7 min per a day (4 times a day)
1^{st} week August	Started fruit harvesting with fertigation (10-10-30 + 3.3 MgO) for 7 min per a day (4 times a day)

The greenhouse growing was limited as it was without a controlling system for temperature and humidity. The recording of the air temperature in the greenhouse was measured by temperature loggers (Tinytak Talk2, Gemini Data Loggers Ltd., UK) with the sampling period set to 20 min (Figure 6.11). The six temperature loggers were installed in different locations and were tightly attached to bench legs under the bench to avoid sunlight. The recorded temperature inside the greenhouse was reported in terms of mean, maximum and minimum temperatures for each month until the end of the experiment (Table 3.2). Each individual strawberry fruit was gently harvested using a finger picking technique, including the cap and short stem. The marketable grade fruits were harvested in the early morning from 6.00 to 8.00 am. The fruit maturity of this study was considered by a uniform size and fruit weight >10 g, full red colour with total soluble solids content (TSS) around 8%.

Table 3.2: Temperatures (^{o}C) inside greenhouse at Writtle College during the winter cultivation in 2014 and 2015 and the summer cultivation in 2014.

Year	**Temperature (^{o}C)**						
	The 1st winter cultivation				***The summer cultivation***		
2014	**February**	**March**	**April**	**May**	**June**	**July**	**August**
Mean	11.00	14.28	17.95	20.93	23.09	24.89	21.28
Max	38.61	45.02	48.14	53.02	46.01	50.92	44.15
Min	1.39	-1.09	1.61	1.86	11.78	10.31	7.96
2015	***The 2nd winter cultivation***						
Mean	8.70	11.83	15.64	17.70			
Max	27.60	40.45	42.94	39.05			
Min	-1.44	-1.45	1.52	-1.48			

(A1)

(A2)

(B)

Figure 3.1: Strawberries cv. ‘Elsanta’ and ‘Sonata’ cultivated during February to April (the 1st winter cultivation) for 72 days (first harvesting) in 2014 (A1-A2) and (the 2nd winter cultivation) (B) for 75 days (first harvesting) in 2015. *Source*: Chaiwong (2015).

(A)

(B)

Figure 3.2: Strawberries cv. ‘Elsanta’ and ‘Sonata’ cultivated during June to July in 2014 (the summer cultivation) for 36 days (first harvesting). *Source*: Chaiwong (2015).

Strawberries were directly harvested from the greenhouse at the maturity index as described in plant materials. Individual fruits were randomly selected and allocated for packing in 250 g commercial polyethylene terephthalate (PET) vented punnets (105 x 170 x 60 mm) with a small piece of bubble sheet (75 mm x 125 mm) (Figure 3.3).

Figure 3.3: 'Elsanta' and Sonata' strawberries packed in PET punnet. *Source*: Chaiwong (2015).

Packed fruits were carried to the postharvest laboratory within 2 hours of harvest. Room cooling started within 4 hours and the pulp temperature dropped to the range of 5.0-7.0^{o}C (±1^{o}C). The cooled punnet was top sealed with commercial plastic film with 6 perforations of 8 mm diameter (Adare Advantage Ltd) (Figure 3.4).

Figure 3.4: 'Elsanta' strawberries packed in PET punnet before impact and vibration tests. *Source*: Chaiwong (2015).

3.3 IMPACT AND VIBRATION TESTS

The experiment was conducted to examine the effect of the impact and vibration tests on the quality and bruise damage of ‘Elsanta’ and ‘Sonata’cutivars. The different impact and vibration conditions were arranged treatments as described in Chapter 4 (section 4.2.1) and Chapter 5 (section 5.2.1), respectively.

3.4 STORAGE CONDITIONS

The treated punnets from the impact and vibration tests were stored at low temperature at 10$\pm$1^{o}C and relative humidity (RH) at 70$\pm$5% RH for 3 days (day 3). Commercially, a shelf-life of strawberries is 3 days after lead time of an transport and distribution for 12-24 hr (Terry *et al.*, 2011)

3.5 QUALITY DETERMINATION

Strawberry quality was determined immediately after vibration and impact tests (day 0) and after 3 days from low temperature at 10$\pm$1^{o}C and relative humidity (RH) at 70$\pm$5% RH (day 3).

3.5.1 Percentage of quality category and severity bruise determination

Percentage of quality category was calculated for the number of fruits in each damage area (undamaged, dry, and wet bruises). The descriptors for individual severity of bruises were adapted from Fischer *et al.* (1992). They ranged from undamaged level (score 5) to very severely damage level and mould formation (score 1). Figure 3.5 further shows the severity of bruises of strawberries described by percentage of bruise area, dry bruise and wet bruise. A limiting quality factor was considered the severity score of 3 as the limit of acceptable quality.

3.5.2 Measurement of electrical conductivity and fruit weight

Electrical conductivity (EC) was evaluated and adapted using the method of Jiang *et al.* (2001). The controlling number of sample fruits was based on approximate fruit weight. Five fruits (winter cultivation) or eight fruits (summer cultivation) in each punnet from storage at Day 0 and Day 3 were immersed in 500 ml of distilled water in a 600 ml beaker. The sample temperature in the distilled water was controlled at 25^{o}C for 10 min using a water bath (Phillip Harris, UK). The immersed fruits were gently stirred for 5 sec before the determination of EC value. The EC test was recorded with a handheld conductivity meter (CyberScan CON 110, Eutech Instruments, USA) (Figure 3.6) and expressed as µS.

To determine fruit weight, three fruit samples from each punnet were randomly and individually weighed by a digital balance (Mettler PE 600, Precisa Balances Limited, UK).

3.5.3 Weight loss (%)

A strawberry punnet held in storage condition for 3 days was weighed daily with the percentage weight loss calculated by using the formula:

$$\text{Weight loss (\%)} = \frac{\text{Initial weight} - \text{Final weight}}{\text{Final weight}} \times 100$$

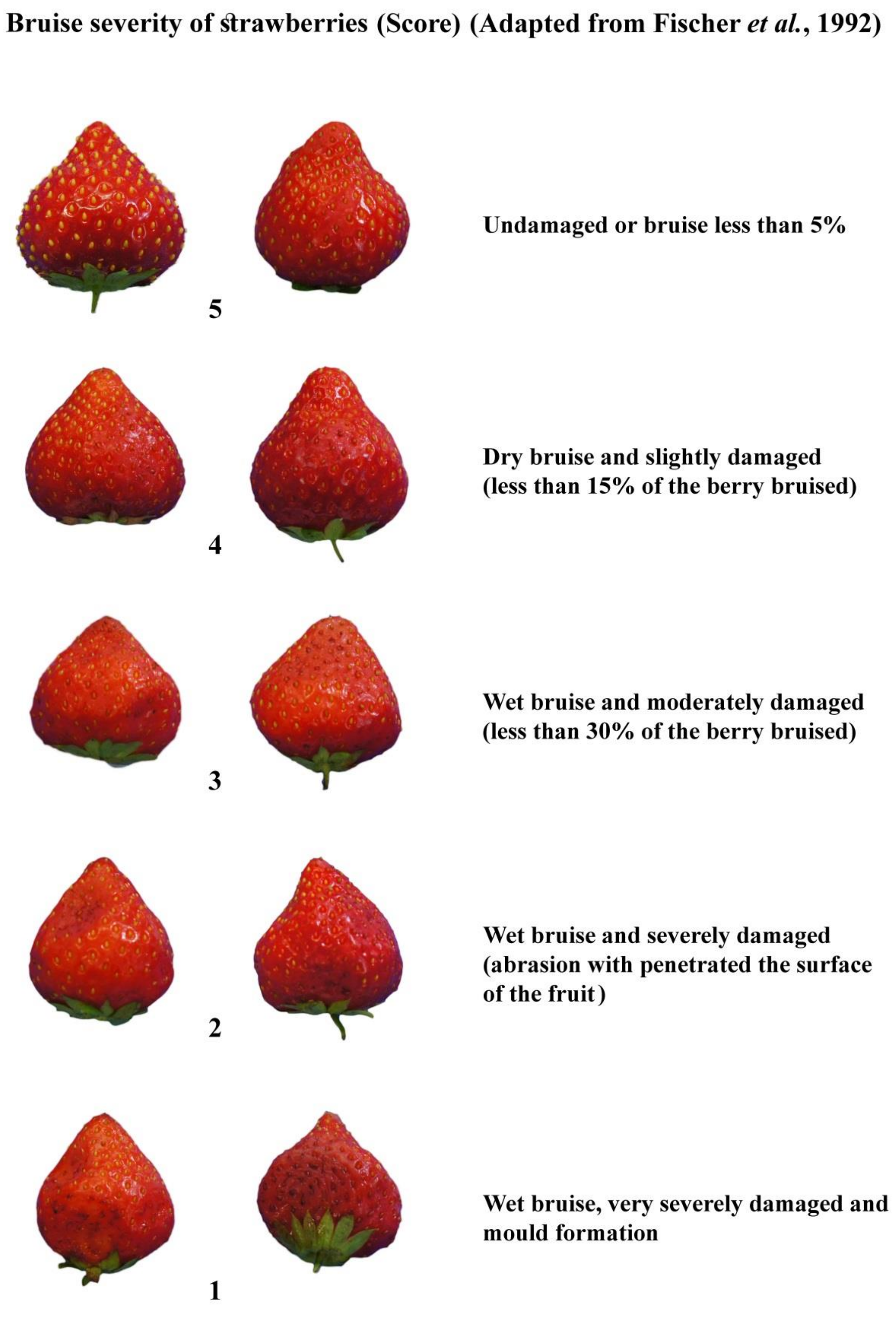

Figure 3.5: The bruise severity of strawberries from 5 (undamaged level) to 1 (very severe damage level). *Source*: Chaiwong (2015)

3.5.4 Firmness (puncture and compression tests)

The middle position of strawberry fruit (3 fruits per punnet) was used to determine fruit firmness from the maximum peak of force (kg) using a fruit texture analyser GS-20 (GüSS Manufacturing (Pty) Ltd, South Africa) (Figure 3.7). The speed of measurement was at 10 mm/sec with an 8 mm cylinder probe (a puncture test) and a 42 mm compression platen (a compression test) for 8.9 mm (a measured distance).

3.5.5 Colour measurement

The colour measurement of fruit was determined only for summer production. For the fruit surface colour of three fruits per punnet, three readings from different middle positions on each fruit were measured using the Chroma Meter (Minolta CR200, Japan) as expressed in L*, a*, b* CIE Chromaticity values. L* value presents dark to light on the scale of 0-100. Red to green colour indicates (+a*) to (-a*) value while yellow to purple colour indicates (+b*) to (-b*). Hue angle (h*) and chroma (C*) were calculated as described in the formula to represent the colour intensity and actual colour or redness, respectively.

$$C^* = \sqrt{a^{*2} + b^{*2}}$$

$$h^* = \tan^{-1}\left(b^* / a^*\right)$$

Figure 3.6: Handheld conductivity meter (CyberScan CON 110) for electrical conductivity measurement. *Source*: Chaiwong (2015).

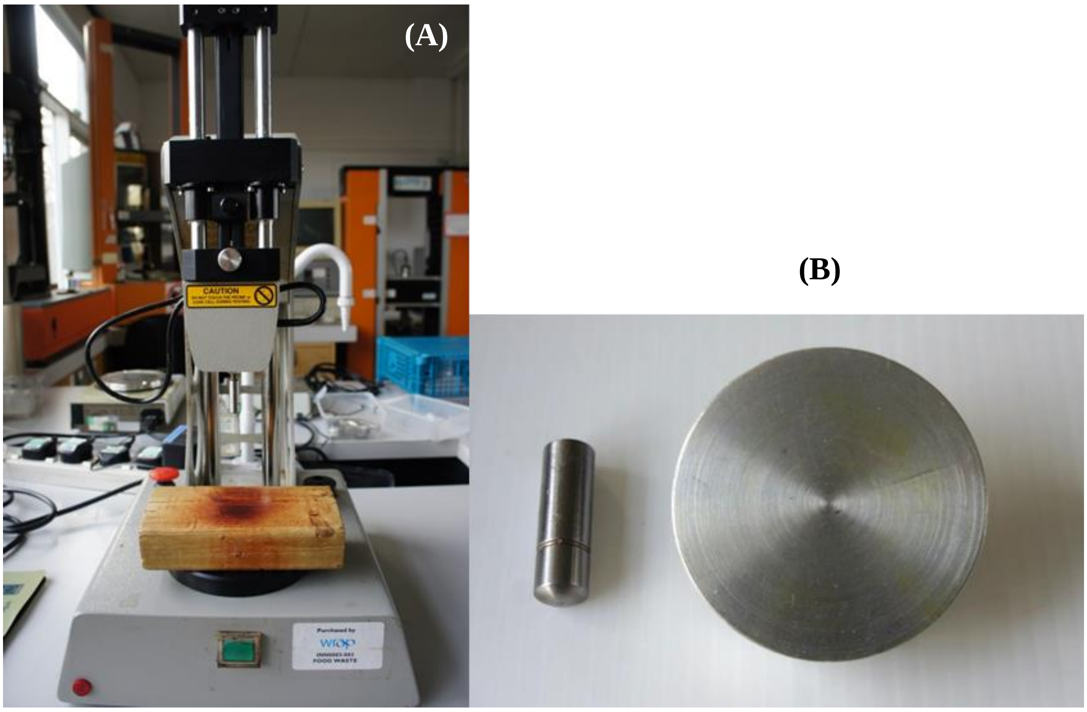

Figure 3.7: Fruit texture analyser GS-20 with a diameter size of cylinder probe (8 mm) (A) and compression platen (42 mm) (B). *Source*: Chaiwong (2015).

3.5.6 Measurements of total soluble solids (TSS), titrable acidity (TA) and TSS: TA ratio

Six strawberries in each punnet were randomly selected for the measurements of TSS, TA, and TSS: TA ratio. The sample fruit was cut into four identical portions, two pieces in each fruit were squeezed for the juice sample. The clear strawberry juice was measured the total soluble solids (TSS) with a digital pocket refractometer (PAL-1, Atago, Japan). Titratable acidity (TA) was measured by titration of strawberry juice with 0.1 M sodium hydroxide (NaOH) and expressed as citric acid (%w/w) (AOAC, 1990). Also, the TSS and TA contents were presented in a ratio of TSS and TA levels.

$$\% \text{ acid (w/v)} = \frac{V_1 \times N \times Eq \times 100 \times F}{Vs \times 1000}$$

Where;

V_1	=	Volume of 0.1 NaOH used for titration (ml)
N	=	Extract concentration of 0.1 N NaOH (N)
Eq	=	Equivalent weight of acid (g), Eq for citric acid anhydrous = 64.04
100	=	Conversion factor from 1 ml to 100 ml
Vs	=	Volume of sample taken to analyze (ml)
1000	=	Conversion factor from mole to molar

3.5.7 Respiration rate measurement

‘Elsanta’ and ‘Sonata’ strawberries from the summer cultivation (2014) and the 2nd winter cultivations (2015) were used for respiration rate measurement. Respiration rate measurements of ‘Elsanta’ and ‘Sonata’ were carried out by static system. The preparation of punnet samples before the impact and vibration test was described in the section 3.2 (plant materials). In addition, treatments in the impact and vibration tests were also explained in Chapter 4 (section 4.2.2) and chapter 5 (section 5.2.2), respectively.

Strawberries were approximately packed 250 g in PET punnet. After the vibration and impact tests, the sample punnet was placed in a plastic food container (3,800 ml). A total of 3 replicates (summer) and 5 replicates (winter) were used in each treatment. The sample punnet was stored at low temperature (10$\pm$1^{o}C) and relative humidity (RH) at 70±5% RH for 96 hours (day 4). CO_2 production (%) was measured using a combo gas analyzer (David Bishop instruments, Ltd, UK). As shown in Figure 3.8, CO_2 gas determination of strawberry punnet was taken by inserting needles through a septum of 15 mm diameter into container by a needle 60 mm in length. The CO_2 concentration (%) was read until a constant value, usually within 10-15 sec. The collection time of gas accumulation was two hours and gas sampling was measured at 0, 4, 16, 24 (day 0), 48 (day 2), 72 (day 3) and 96 hours (day 4). The respiration rate was calculated and reported in mgCO_2/kg.hr using the formula stated in Salveit (2015).

$$\text{Respiration rate (mg } CO_2\text{/kg.hr)} = \frac{CO_2 \text{ (\%) x Volume (ml) x 1.89}}{\text{Fruit weight (kg) x Length of time (hr)}}$$

Where;

CO_2 = Carbon dioxide concentration after closing container for 2 hours (%)

Volume = Volume of container (ml)

Fruit weight = Strawberry weight (kg)

Length of time = Closing container (hr)

1.89 = Conversion figure of CO_2 at 10^{o}C

Furthermore, percentage of quality category and severity bruise were also counted after storage at 10^{o}C for 4 days using the same bruise detection method as seen in Figure 3.5.

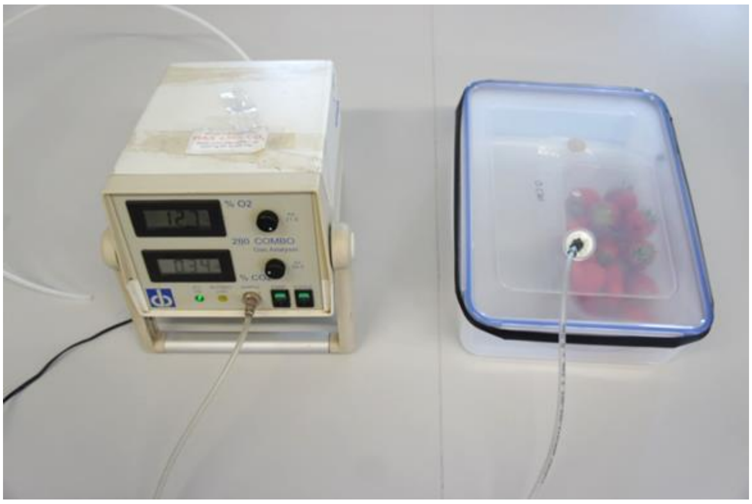

Figure 3.8: Respiration rate measurement of strawberries by static system. *Source*: Chaiwong (2015).

3.6 DATA ANALYSIS

The experimental design in the impact and vibration tests was undertaken using a completely randomized design (CRD). Treatment conditions in impact and vibration tests were described in Chapter 4 (section 4.2.2) and Chapter 5 (section 5.2.2), respectively. For statistical analysis, analyses of variance and correlation coefficient (*r*) were performed using SPSS version 16.0. Duncan's multiple range test (DMRT) were calculated at 5% level of significance. The correlation coefficient (*r*) between the selected objective measurements (EC, firmness, respiration rate) and the subjective measurements (bruise damage and severity score) was calculated by Pearson's correlation at a significant level of 1%. Graphic presentation was made using Microsoft Excel 2010 (Microsoft Inc.).

CHAPTER 4

IMPACT TEST ON THE QUALITY AND DAMAGE TO 'ELSANTA' AND 'SONATA' STRAWBERRIES IN THE WINTER AND SUMMER CULTIVATIONS

4.1 INTRODUCTION

The impact test of fruits from a specific height is associated with impact energy, which depends on fruit weight and drop height (Ruiz-Altisent and Moreda, 2011). Factors found to have influenced fruit bruise have been explored in several studies such as the drop heights, contact surface materials, and a number of drops (Kitthawee *et al.*, 2011; Maness *et al.*, 1992; Sinobas *et al.*, 1991; Shafie *et al.*, 2015; Unuigbe and Onuoha, 2013; MacLeod *et al.*, 1976; Lu *et al.*, 2012). The range of drop height for the berry fruit test was 50 to 1200 mm, whereas a drop test for an individual or packed strawberry has been conducted with a height of 50 to 380 mm (Ferriera *et al.*, 2008; Kitazawa *et al*., 2014). However, there is currently no study in the impact test of strawberry punnet or clamshell on bruise damage and quality of strawberries.

Moreover, a metal material surface of the drop test gave the greatest bruise in various fresh fruits, namely apples, peaches, strawberries and tomato (Unuigbe and Onuoha; Reza, 2013; Ferreira *et al*., 2008; Idah *et al.*, 2007). The number of drops also influenced fruit quality, for example, a number of eight drops enhanced by approximately 50% the respiration rate of mature green tomatoes as compared to control (no drop) (MacLeod *et al.*, 1976). The fruit firmness and colour correlated to bruise volume or area in apples and persimmons (Samim and Banks, 1993; Sinobas *et al.*; 1991; Lee *et al.*, 2005). As far as a bruise indicator from impact force is concerned, the respiration rate measurement by CO_2 production (Burton and Schulte-Pason, 1987; Massey *et al.*, 1982). The puncture test showed a good indicator for impact bruise of peaches (Hung and Prussia, 1989), apples (Sinobas *et al.*, 1991) and persimmons (Lee *et al.*, 2005). Furthermore, the electrical conductivity (EC) technique was suggested to use a bruise assessment in bananas and tomatoes (Bugard *et al*., 2014; Lee *et al*., 2007). So far, however, there has been little discussion about electrical conductivity (EC) technique to determine strawberry bruise from impact test. Previous study of the EC method has dealt with vibration test. Jiang *et al.* (2001) reported that the EC value was significantly related to the percentage of damage index in strawberries. No previous study has investigated the EC method to evaluate strawberry bruise from impact test and to compare the EC technique with firmness and respiration rate measurements as using a bruise indicator of strawberries.

In this study, a drop height was a key factor affecting on the quality and bruise of 'Elsanta' and 'Soanata' strawberries, including other concerning factors such as a period of storage, a seasonal cultivation (winter and summer).

Therefore, the hypotheses of this impact test are:

a) there will be a higher level of damage on summer grown crops of 'Elsanta' and 'Sonata' cultivars than winter grown.
b) There will be no difference in impact bruise between 'Elsanta' and 'Sonata' cultivars.
c) An increase in drop height will give an increase in impact bruise for both cultivars and both cultivation seasons after cool storage.
d) In terms of a bruise indicator and a predictor, the EC technique will give a greater correlation than firmness tests and respiration rate measurement to bruised strawberries after an impact test and cool storage.

In the previously published research, there has been no impact study of a whole strawberry punnet by a drop test with different height levels. There is a lack of research focused on the drop test of strawberry punnets in different heights and the correlation between the objective methods of bruise determinations (EC method, firmness tests and respiration rate measurement) and subjective methods using bruise incidence and visual score. Thus, the research described in this chapter focused on the effect of the drop height of impact test on the quality and bruise of packed 'Elsanta' and 'Sonata' strawberries in the punnet during the winter and summer cultivations. The relationship between the selected objective methods (physical properties) and bruise incidence by subjective method to develop a bruise indicator of strawberries.

4.2 MATERIALS AND METHODS

4.2.1 Fruit materials

'Elsanta' and 'Sonata' fruits were hand-picked and harvested when they fully had a red colour from the greenhouse at Writtle College during the winter and summer cultivations in 2014 (Figures 3.1 and 3.2). Additionally, two cultivars were planted during the winter season in 2015 for the respiration rate trial. The fruit sample preparation has been described in Chapter 3 (general materials and methods) (section 3.2). Briefly, the fruits were packed in PET punnets with a packing size of 250 g and cooled by room cooling method for 4 hours. Cooled punnets were top sealed and these were carried out within a maximum of an hour after removal from the room cooling.

4.2.2 Effect of the height levels of impact test on the quality of packed strawberries in punnet

The cooled punnet of strawberries was randomly allocated to treatments prior to the impact test. The effect of the impact test on the quality and damage on the strawberry punnet was determined at the different height levels: 0, 250, 500, 750 and 1000 mm onto mild steel (thickness of 31.0 mm) for five consecutive drops (Figure 4.1), to simulate five events of punnet drop during strawberry handling (Figure 7.2). The impact energy (J) was calculated using the formula: $E=mgh$. Where m denotes the packed strawberry mass (approximate 250 g per punnet); g denotes acceleration of gravity (9.81 m/s^2); h denotes drop height (m) (Ruiz-Altisent and Moreda, 2011). Therefore, the equivalent impact energy levels (J) for four height were 0.613 J (250 mm), 1.226 J (500 mm), 1.839 J (750 mm) and 2.453 J (1000 mm). The experimental plan of this study was undertaken using the completely randomized design (CRD) with five (the winter cultivation) or four (the summer cultivation) punnets (replicates). The impact test was conducted for each strawberry cultivar in the winter cultivation and was repeated in the summer cultivation in 2014.

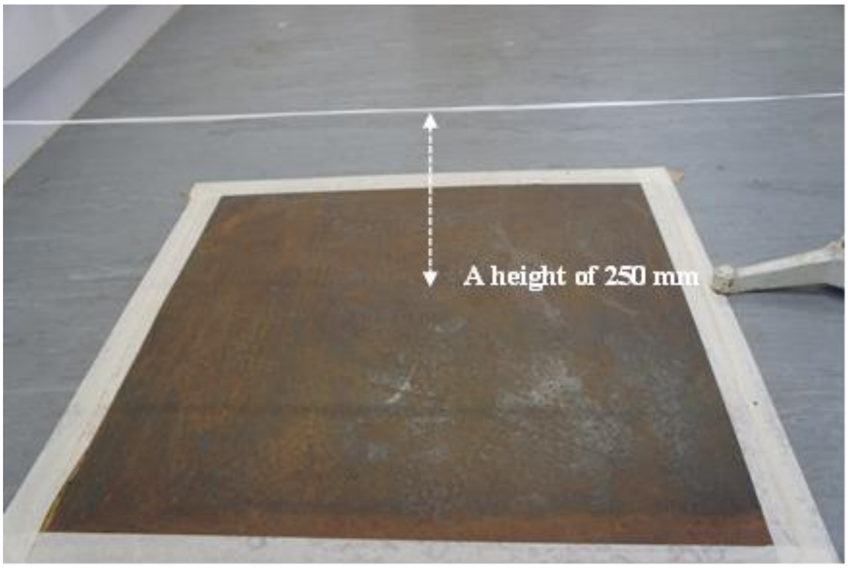

Figure 4.1: Impact test of strawberry punnet onto the mild steel. *Source*: Chaiwong (2015).

4.3 QUALITY DETERMINATION OF THE PACKED STRAWBERRIES FROM THE FIVE HEIGHT LEVELS

After the impact test, the quality and damage of the strawberry punnet was determined immediately (day 0), and after storage at 10±1^{o}C, with relative humidity (RH) at 70±5% (day 3). Briefly, the physicochemical properties were measured as explained in the Chapter 3 (section 3.5), including visual assessment for bruise damage and severity score. Additionally, the respiration rate of strawberries also was measured as explained in Chapter 3 (section 3.5.6) and CO_2 production (%) was measured using a combo gas analyzer (David Bishop Instruments, Ltd, UK) after the impact test and the storage at 10^{o}C for 4 days.

4.4 DATA ANALYSIS

Mean comparisons in each strawberry cultivar and cultivation were performed using Duncan's multiple range test (DMRT) at $p \leq 0.05$, whereas the correlation coefficient (r) between the four objective methods (EC method, firmness tests, and respiration rate measurement) and bruise damage was performed using Pearson's correlation at $p \leq 0.01$.

4.5 RESULTS

4.5.1 Temperature in the greenhouse during reproductive growth of 'Elsanta' and 'Sonata' strawberries in the winter and summer cultivations during 2014-2015

During the winter and summer periods in 2014 and 2015, the temperatures in the greenhouse for 'Elsanta' and 'Sonata' cultivations were recorded until the last day of the trial and are shown in Table 3.2. In the first winter production in 2014, the range of average temperature within the four months (February to May) was 11.00 to 20.93^{o}C. In the second winter cultivation in 2015, the range of average temperature in the same period was 8.70 to 17.70^{o}C, which was lower by around 3^{o}C than in 2014. The summer production during three months (June to August) had a higher average temperature (21.28 to 24.89^{o}C) than the winter production. At around 12.00 hr for each month, the highest greenhouse temperature of the first and second cultivations in the winter season occurred in May (53.02^{o}C) and in April (42.94^{o}C), respectively. The maximum temperature in the summer production was approximately 50^{o}C in July. The minimum temperature during the winter period in 2014 and 2015 showed approximately 1.5^{o}C and -1.5^{o}C, which were lower than the summer cultivation by around 10^{o}C.

4.5.2 The effect of impact test on the quality, bruise and respiration rate of 'Elsanta' strawberries

4.5.2.1 Percentage of quality category and electrical conductivity of 'Elsanta' strawberries

The preharvest conditions from the winter and summer seasons in 2014 were considered and these directly affected the percentage of bruises and electrical conductivity values in 'Elsanta' strawberries (Figures 4.2 and 4.3). The initial fruit quality before impact test gave undamaged fruits in punnet in the winter (100%) and in summer (90%) cultivations. Immediately after the impact test (day 0), there was a reduction of undamaged fruits from the drop height of 250 mm to 60% (winter) and 36% (summer). A rise in the height level affected notably the percentage of wet bruise, particularly at 1000 mm (2.453 J) in the winter (60%) and summer (80%) ($p \leq 0.05$) (Figures 4.2A and 4.3A). There were no undamaged fruits in the summer cultivation from the drop heights of 750 mm (1.839 J) and 1000 mm (2.453 J) (Figure 4.3A).

The electrical conductivity (EC) also related to an increase of drop height. The EC value of undamaged fruits in winter production (6.8 µS) was less than in the summer period (20 µS). The punnet dropped from 1000 mm increased significantly the highest EC values with 36.5 µS (winter) and 80 µS (summer) ($p \leq 0.05$) (Figures 4.2A and 4.3A). After storage at 10°C for 3 days, mould and rot incidences were not found in either strawberry harvestings. Control (no drop) was still observed to have a dry bruise incidence of around 40% (winter) and 80% (summer) after storage (Figures 4.2B and 4.3B).

When compared to the different drop height, the percentage of dry bruise from a height of 250 mm increased to around 55% when compared to the initial day (Figures 4.2B). There was not a significant dry bruise between control and the drop height of 250 and 500 mm ($p > 0.05$) (Figures 4.3B). A drop height of 1000 mm gave the greatest percentage of wet bruise (80%) ($p \leq 0.05$) (Figure 4.2B and 4.3B). The low temperature storage affected a reduction of EC value when compared to the first day, especially for a height of 1000 mm (2.453 J) (Figures 4.1B and 4.2B).

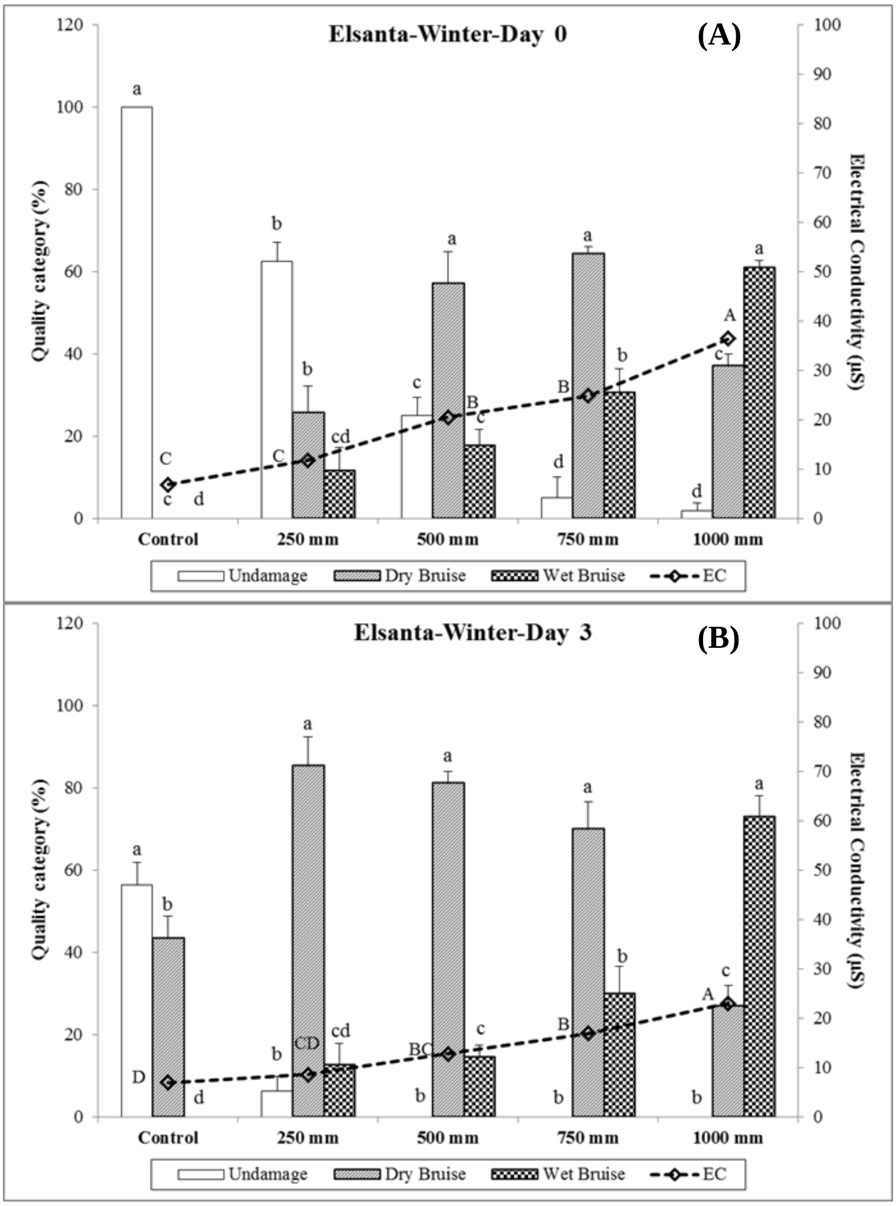

Figure 4.2: Effect of impact test on quality category and electrical conductivity of 'Elsanta' strawberries from the winter cultivation at day 0 (A) and day 3 (B). Different letters in the different heights for DMRT test indicate significant differences at $p \leq 0.05$. Values are the mean ±S.E. from 5 replicates.

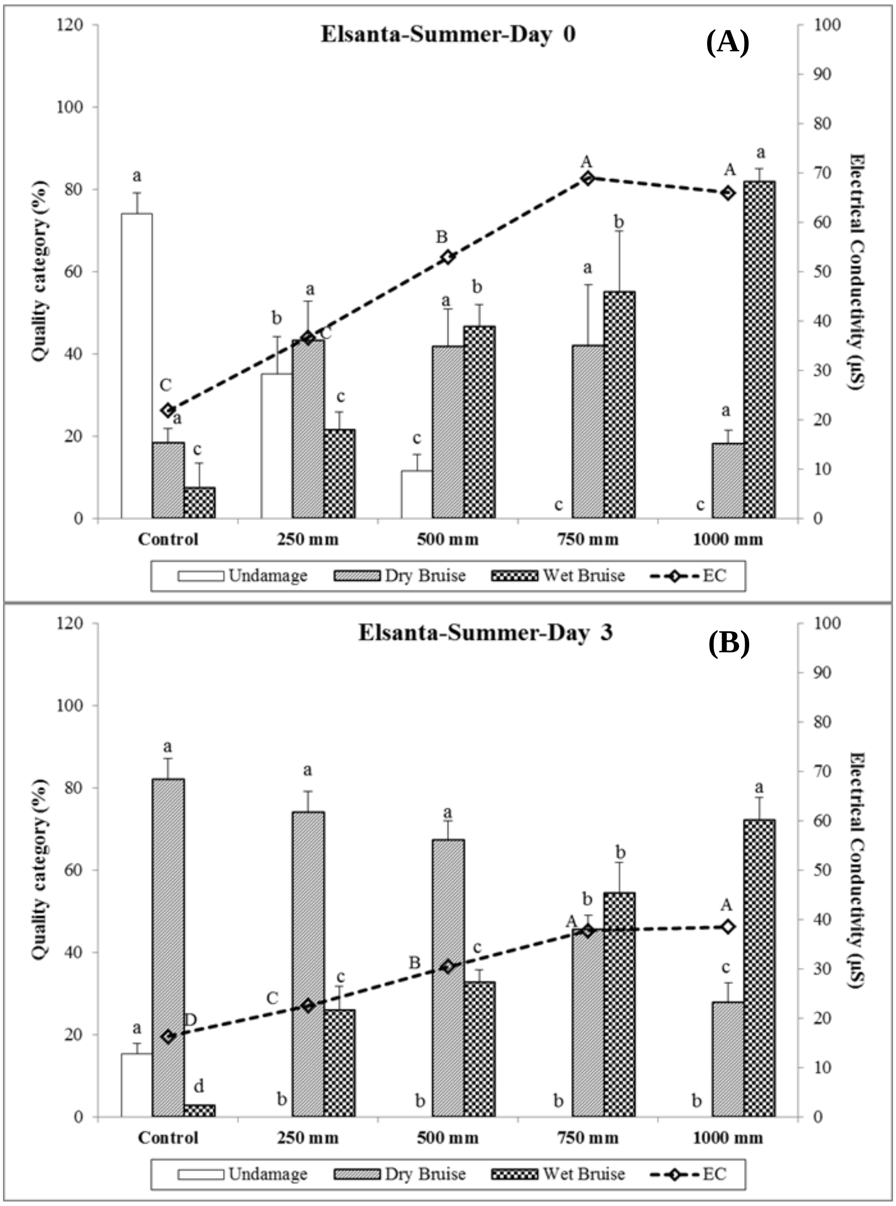

Figure 4.3: Effect of impact test on quality category and electrical conductivity of 'Elsanta' strawberries from the summer cultivation at day 0 (A) and day 3 (B). Different letters in the different heights for DMRT test indicate significant differences at $p \leq 0.05$. Values are the mean ±S.E. from 4 replicates.

4.5.2.2 Fruit weight, firmness (puncture and compression) and severity score of Elsanta' strawberries

The uniformity of fruit size in 'Elsanta' strawberries was evaluated by fruit weight as opposed to dimensions. The average fruit size from the winter cultivation was bigger than from the summer production by approximate 7 g in each fruit. The maximum diameter of the equatorial section with the approximate fruit weight of 20 g and 12 g was 35 mm and 31 mm, respectively (data not shown). In this study, there was no significant difference in fruit weight among the five treatments (Table 4.1).

As shown in Table 4.1, the fruit firmness was evaluated by both puncture and compression tests. As expected, an increase in drop height significantly reduced strawberry firmness in both cultivations ($p \leq 0.05$). In the winter production, control treatment (no drop) had the highest puncture and compression values of strawberries, as compared to the punnet dropped from 250 to 1000 mm, after the impact test at day 0 and by the end of storage ($p \leq 0.05$). The lowest firmness value was found for a height of 1000 mm ($p \leq 0.05$).These results of fruit firmness during winter cultivation also agreed with those results from the summer production. Additionally, the findings from the puncture test could detect a greater difference in firmness value than the compression test. The punnet dropped from 1000 mm gave the minimum severity score from both seasons with a score below 3 ($p \leq 0.05$). Overall, a height level at 500 mm provided a severity score over 3 level.

4.5.2.3 TSS (%), TA (%) and TSS:TA ratio of 'Elsanta' strawberries

The results of TSS, TA and TSS:TA contents are shown in Figures 4.4 and 4.5. In the winter cultivation, TSS and TA contents of 'Elsanta' strawberries were over 8% and 0.9%, respectively, while the summer cultivation produced strawberries with the lower TSS (approximate 7.5% TSS) and higher TA (approximate 1% TA) contents when compared with the winter cultivation. However, the impact test had no the effect on TSS, TA and TSS:TA levels among the five treatments in both seasons and both storage conditions.

Table 4.1: Effect of impact test on fruit weight, firmness and severity score of 'Elsanta' strawberries from the winter and summer cultivations at day 0 and day 3.

Height (mm)	Weight (g)	Puncture (kg)	Compression (kg)	Severity score
Day 0-Winter		***Elsanta-Winter***		
Control	21.43±0.20	0.504^{a}±0.012	1.488^{a}±0.091	4.9^{a}±0.04
250 (0.613 J)	21.72±0.48	0.380^{b}±0.038	1.506^{a}±0.073	4.5^{b}±0.08
500 (1.226 J)	22.45±0.42	0.337^{bc}±0.036	1.394^{a}±0.048	4.1^{c}±0.03
750 (1.839 J)	21.02±0.34	0.259^{cd}±0.013	1.141^{b}±0.083	3.5^{d}±0.08
1000 (2.453 J)	21.37±1.04	0.212^{d}±0.019	1.003^{b}±0.076	2.6^{e}±0.05
Day 3-Winter				
Control	19.51±0.45	0.627^{a}±0.018	1.952^{a}±0.050	4.5^{a}±0.08
250 (0.613 J)	18.96±0.27	0.599^{a}±0.047	1.796^{a}±0.089	3.7^{b}±0.13
500 (1.226 J)	20.18±0.29	0.402^{b}±0.024	1.860^{a}±0.089	2.8^{c}±0.22
750 (1.839 J)	19.80±0.23	0.307^{d}±0.012	1.490^{b}±0.082	2.2^{d}±0.07
1000 (2.453 J)	20.32±0.60	0.254^{d}±0.022	1.273^{b}±0.069	1.4^{e}±0.07
Day 0-Summer		***Elsanta-Summer***		
Control	14.50±1.14	0.362^{a}±0.020	1.266^{a}±0.067	4.8^{a}±0.05
250 (0.613 J)	14.94±0.09	0.323^{ab}±0.015	1.176^{ab}±0.100	4.4^{b}±0.06
500 (1.226 J)	15.67±0.71	0.324^{ab}±0.020	1.197^{ab}±0.070	3.8^{c}±0.11
750 (1.839 J)	15.10±1.16	0.298^{ab}±0.015	1.072^{ab}±0.034	3.1^{d}±0.16
1000 (2.453 J)	14.52±0.84	0.262^{b}±0.020	1.103^{b}±0.067	1.8^{e}±0.11
Day 3-Summer				
Control	12.75±0.88	0.436^{a}±0.012	1.441±0.055	4.2^{a}±0.09
250 (0.613 J)	12.67±0.67	0.392^{ab}±0.018	1.412±0.041	3.6^{b}±0.06
500 (1.226 J)	12.25±0.51	0.395^{ab}±0.029	1.381±0.050	3.2^{bc}±0.05
750 (1.839 J)	12.05±0.62	0.358^{bc}±0.025	1.390±0.034	3.1^{bc}±0.06
1000 (2.453 J)	12.21±1.04	0.315^{c}±0.007	1.297±0.070	2.7^{c}±0.35

Means with different letters in the same column at each day are significantly different at $p \leq 0.05$. Values are the mean ±S.E. from 5 replicates (winter) and 4 replicates (summer).

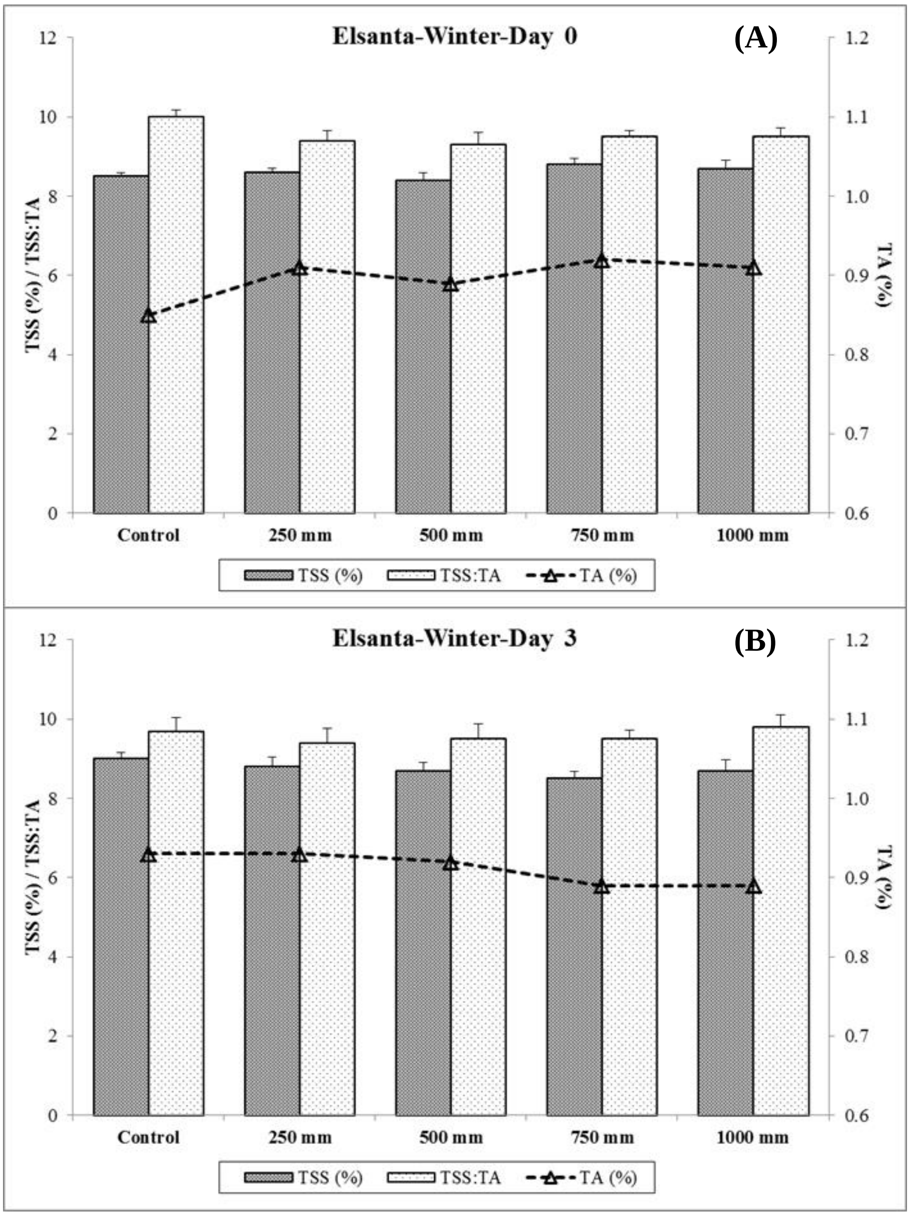

Figure 4.4: Effect of impact test on TSS (%), TA (%) and TSS:TA ratio contents of 'Elsanta' strawberries from the winter cultivation at day 0 (A) and day 3 (B). Different letters in the different heights for DMRT test indicate significant differences at $p \leq 0.05$. Values are the mean ±S.E. from 5 replicates.

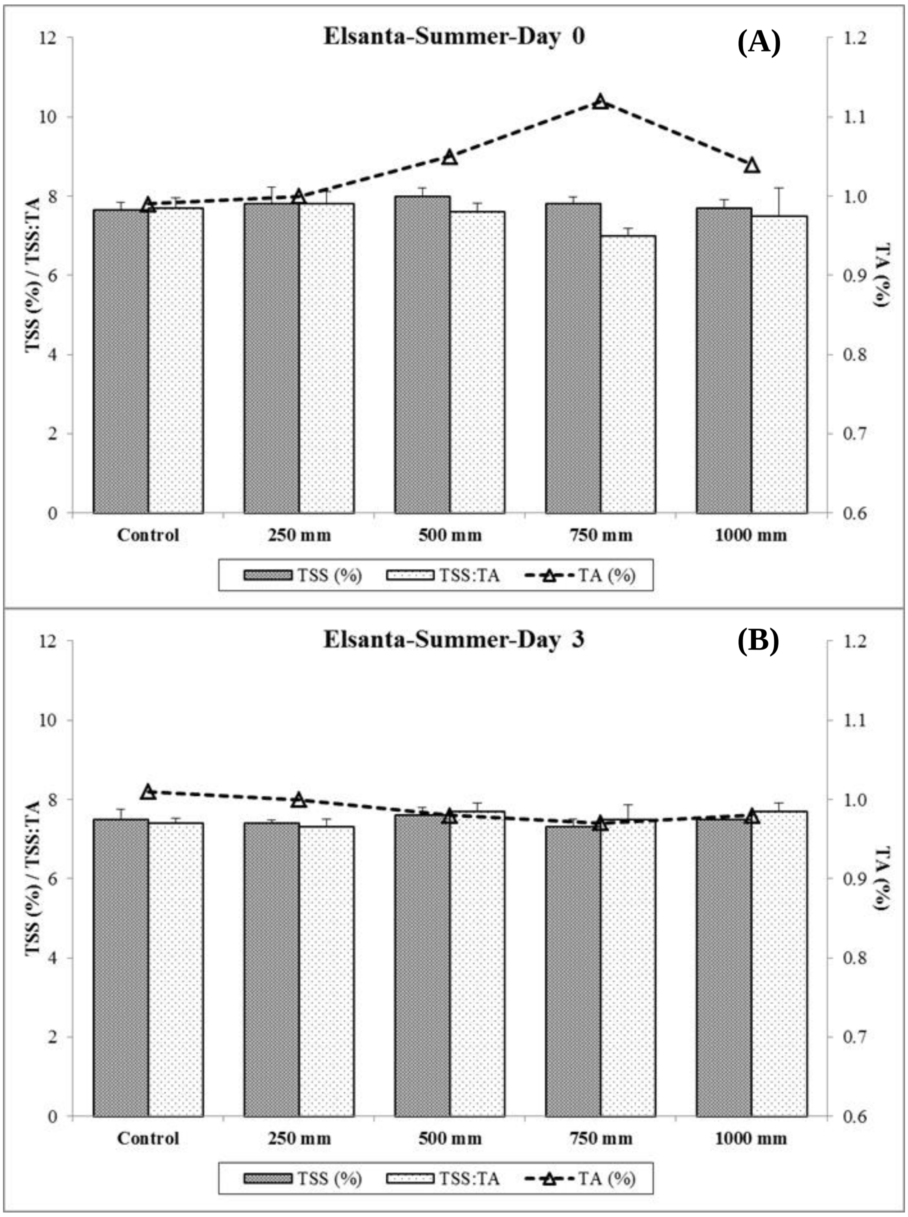

Figure 4.5: Effect of impact test on TSS (%), TA (%) and TSS:TA ratio contents of 'Elsanta' strawberries from the summer cultivation at day 0 (A) and day 3 (B). Different letters in the different heights for DMRT test indicate significant differences at $p \leq 0.05$. Values are the mean ±S.E. from 4 replicates.

4.5.2.4 Fruit surface colour (L*, a*, b*, h*, and C* values) of 'Elsanta' strawberries

The colour determination of fruit surface was carried out only for the summer cultivation. Figure 4.6 shows that there was a gradual decline in the values of all colour attributes from a higher drop height. The drop height had no the effect on h* value at day 0 and day 3 ($p>0.05$). The punnets dropped from the heights of 750 mm and 1000 mm had the lowest colour values (L*, a*, b* and C*) ($p\leq0.05$). The a* (redness) and L* (lightness) values of strawberries increased slightly after storage at 10^{o}C for 3 days.

4.5.2.5 Weight loss (%) of 'Elsanta' strawberries

Weight loss (%) of 'Elsanta' strawberries was evaluated for 3 days during storage at 10^{o}C. As shown in Table 4.2, overall there was no the effect of height level on the weight loss of 'Elsanta' strawberries from the winter and summer cultivations ($p\leq0.05$). At the end of storage at 10^{o}C and 70%RH for 3 days, weight loss (%) of the winter strawberries (approximate 3.5%) was higher than for the summer strawberries (approximate 1.5%).

Table 4.2: Effect of impact test on weight loss (%) of 'Elsanta' strawberries from the winter and summer cultivations during storage at $10^{o}C$ for 3 days.

	Weight loss (%) (Elsanta)		
Height (mm)	**Day 1**	**Day 2**	**Day 3**
Winter			
Control	1.53±0.13	2.37±0.14	3.09±0.27
250 (0.613 J)	1.71±0.17	2.64±0.17	3.48±0.35
500 (1.226 J)	1.79±0.20	2.80±0.17	3.67±0.34
750 (1.839 J)	1.78±0.26	2.73±0.24	3.55±0.32
1000 (2.453 J)	1.98±0.37	2.82±0.37	3.62±0.45
Summer			
Control	1.05^{a}±0.02	1.74±0.02	1.95±0.02
250 (0.613 J)	1.00^{ab}±0.13	1.71±0.22	1.92±0.25
500 (1.226 J)	0.85^{ac}±0.50	1.40±0.13	1.67±0.12
750 (1.839 J)	0.77^{bc}±0.05	1.37±0.17	1.65±0.15
1000 (2.453 J)	0.72^{c}±0.09	1.20±0.09	1.42±0.11

Means with different letters in the same column at each season are significantly different at $p \leq 0.05$. Values are the mean ±S.E. from 5 replicates (winter) and 4 replicates (summer).

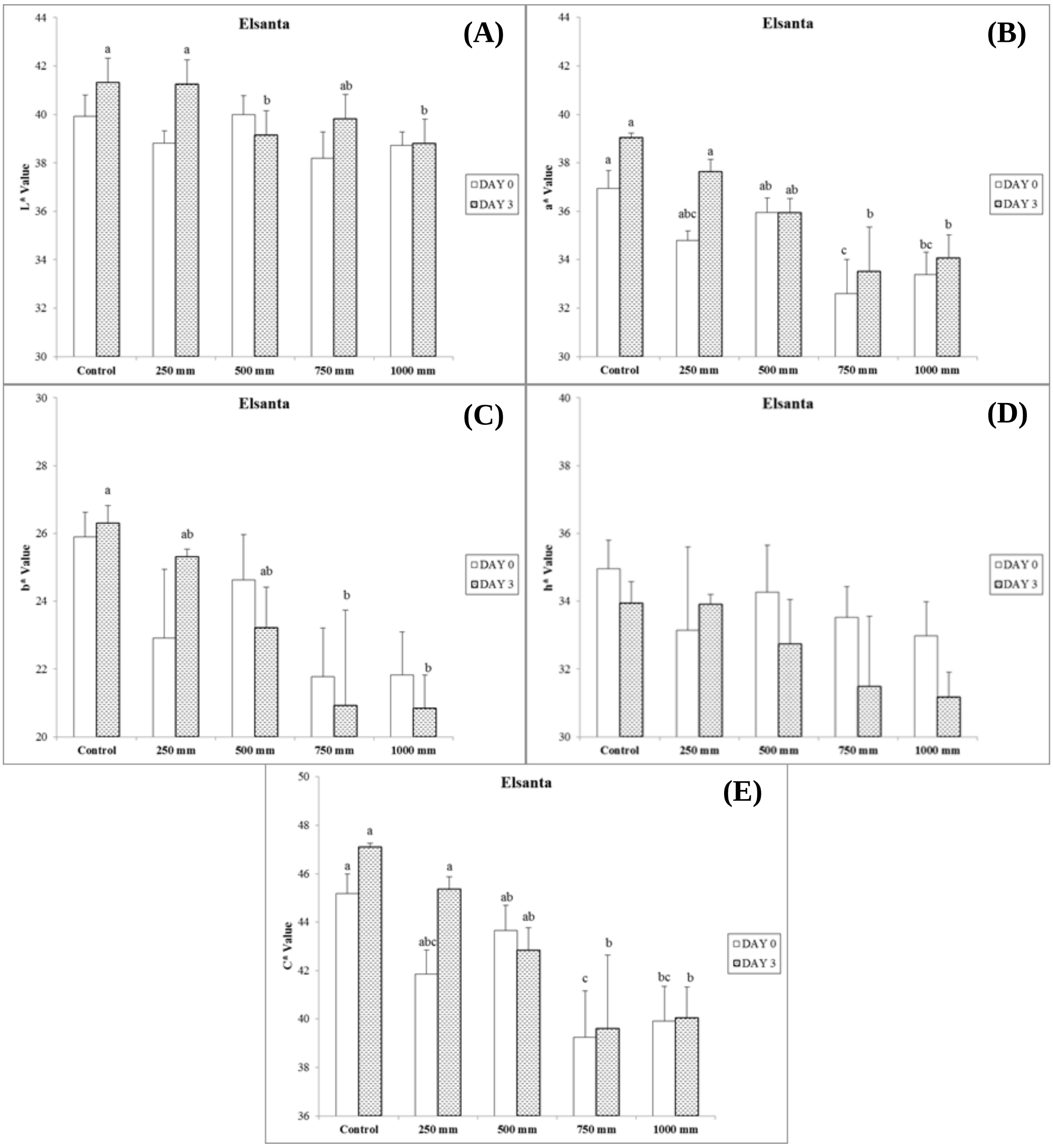

Figure 4.6: Effect of impact test on the values of L* (A), a* (B), b* (C), h* (D) and C* (E) of 'Elsanta' strawberries from the summer cultivation at day 0 and day 3. Different letters in the different heights for DMRT test indicate significant differences at p≤0.05. Values are the mean ±S.E. from 4 replicates.

4.5.2.6 Respiration rate, percentage of quality category and severity score of 'Elsanta' strawberries

The respiration rate of 'Elsanta' strawberries was repeated for the winter production 2015. Before the vibration test, the strawberry maturity was determined such as fruit size, fruit firmness, EC, colour of fruit surface, TSS and TA. The overall quality attributes from the winter production in 2015 had similar value to the last winter cultivation in 2014. For example, the fruit size of 'Elsanta' fruit in 2015 cultivation was approximately selected 20 g per fruit with the same initial EC level (7.86 µS) (data not shown).

As shown in Figures 4.7A-B, the impact damage of 'Elsanta' strawberries from a drop test (250 to 1000 mm) directly affected an increase in respiration rate after day 0. The respiration rate of 'Elsanta' cultivar (control) from the winter production in 2015 (38.87 mgCO_2/kg.hr) was lower than that from the summer production in 2014 (54.44 mgCO_2/kg.hr). In the winter season, on the first day after treatment (0 hour), the punnets dropped from 750 and 1000 mm had the highest respiration rate: approximately 53 mgCO_2/kg.hr, followed by 500, 250 and 0 mm, respectively (Figure 4.7A). Whilst in the summer season, the punnet dropped from a height of 1000 mm also gave the highest respiration rate of 'Elsanta' strawberries (72.56 mgCO_2/kg.hr) (Figure 4.7B). Respiration rates of all treatments gradually decreased within 24 hours and remained steadily over the remaining entire test period (96 hours). At the end of storage, the respiration rates of all treatments were approximately 40 mgCO_2/kg.hr (winter) and 50 mgCO_2/kg.hr (summer) (Figures 4.7A-B).

By the end of storage for 96 hours (4 days), the punnets of the impact test from 250 to 1000 mm had no undamaged fruits. The greatest percentage of wet bruise was found in a height level of 1000 mm ($p \leq 0.05$). The percentage of dry bruise from the height of 250 and 500 mm in the winter cultivation was higher than in the summer cultivation (Figures 4.8A-B). In the storage for 96 hours, however, the mould incidence (summer production) was 17-22% of the total fruits and there was not a significant difference between the impact treatments but higher than control ($p > 0.05$). The severity bruise score reduced a rise of drop height, especially 500 to 1000 mm with a score below 3 in the summer production (Figure 4.8B). In the winter production, the drop test from 750 and 1000 mm also presented a score below 3 (Figure 4.8A). Interestingly, the mould was only observed after at least 72 hours (4 days) but no mould was seen in the first 3 days.

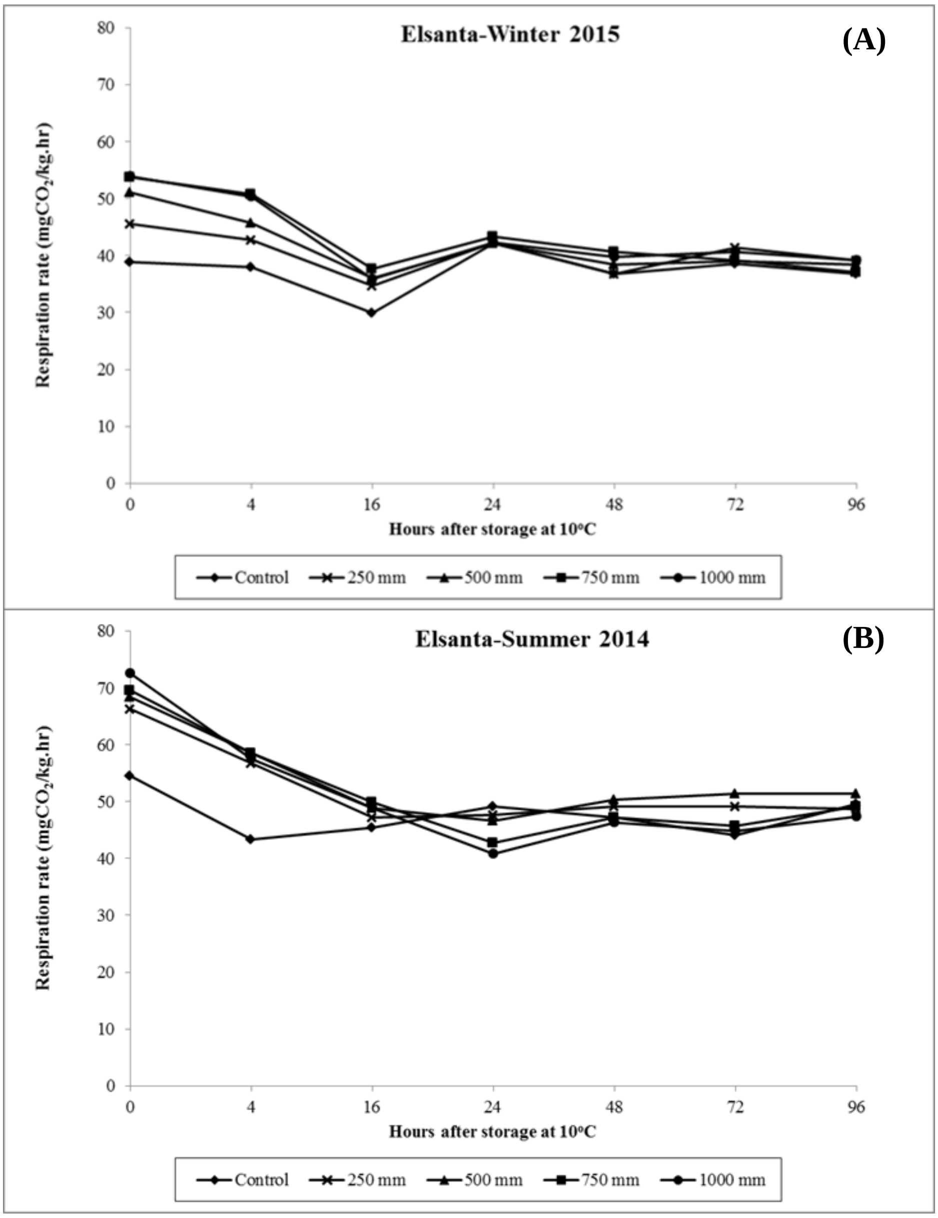

Figure 4.7: Effect of impact test on the respiration rate of 'Elsanta' strawberries from the winter cultivation in 2015 (A) and the summer cultivation in 2014 (B) after storage at 10°C for between 0-96 hours. Values are the mean from 5 replicates (winter) and 3 replicates (summer). The S.E. values of treatments with a range of ± 3.50 (winter) and ± 6.16 (summer) values were not shown due to the overlap in error bars producing a confusing graph.

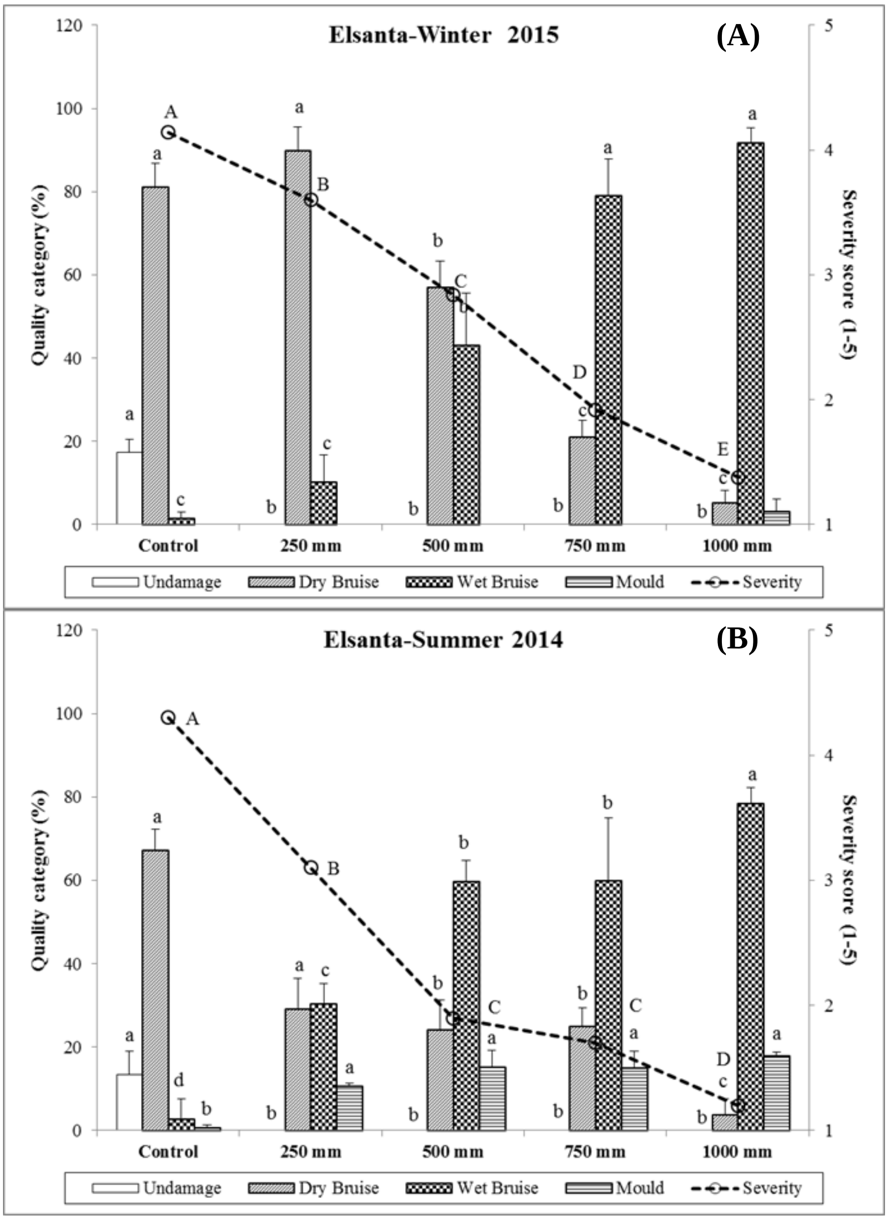

Figure 4.8: Effect of impact test on quality category and severity bruise score of 'Elsanta' strawberries from the winter cultivation in 2015 (A) and the summer cultivation in 2014 (B) after storage at 10°C for 96 hours. Different letters in the different heights for DMRT test indicate significant differences at $p \leq 0.05$. Values are the mean ±S.E. from 5 replicates (winter) and 3 replicates (summer).

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4.5.3 The effect of impact test on the quality, bruise and respiration rate of 'Sonata' strawberries

4.5.3.1 Percentage of quality category and electrical conductivity of 'Sonata' strawberries after impact test

The undamaged fruits of 'Sonata' cultivar after harvesting in the winter and summer productions had a similar level of around 90%. The percentage of undamaged fruits rapidly declined through to the end of storage when it was 35% undamaged (Figures 4.9 and 4.10). In the comparison between 'Sonata' and 'Elsanta' cultivars from the winter production after storage, 'Sonata' strawberries had a percentage of undamaged fruits (35%) (Figure 4.9) which was less than that of 'Elsanta' cultivar (56%) (Figure 4.2). The drop heights of 1000 and 750 mm gave the greatest wet bruise level in the winter (61%) and summer (63%) cultivations, respectively (Figures 4.9 and 4.10). Immediately after the vibration test (day 0), there was no undamaged fruits from a range of drop height (500 to 1000 mm) in the winter season. The punnets dropped from 250, 500 and 750 mm did not have a significant dry bruise in the summer production. The highest EC value was from a drop height of 1000 mm in the summer (76.9 µS) and the lowest value of undamaged fruits in the winter (9.2 µS) ($p \leq 0.05$) (Figures 4.9 and 4.10). On the first day (day 0), the range of EC values in both cultivars was at the same level, from around 7 µS (undamaged fruits) to 80 µS (a height of 1000 mm), as the winter and summer productions (Figures 4.2-4.3 and 4.9-4.10).

At the end of storage for 3 days, the percentage of dry bruise from a height of 0 mm to 500 mm was significantly different ($p \leq 0.05$) (Figure 4.10). In the summer cultivation, the EC value gradually reduced over the entire storage time from around 18 µS (no drop) and 40 µS (at 1000 mm) (Figure 4.10), which were higher than those values in the winter cultivation (Figure 4.9). Overall, the EC values of 'Elsanta' and 'Sonata' cultivars from the winter and summer cultivations had a similar level from all drop heights (Figures 4.2-4.3 and 4.9-4.10).

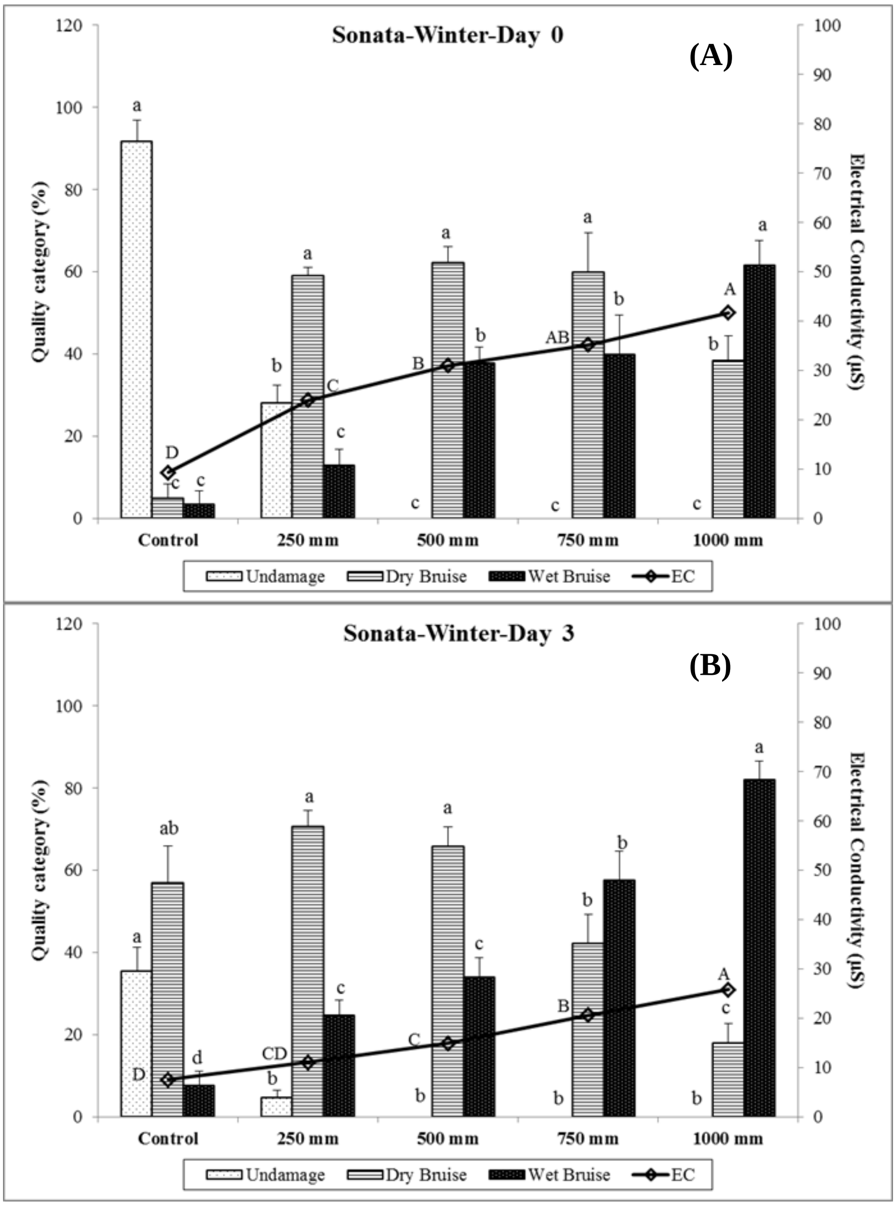


Figure 4.9: Effect of impact test on quality category and electrical conductivity of 'Sonata' strawberries from the winter cultivation at day 0 (A) and day 3 (B). Different letters in the different heights for DMRT test indicate significant differences at $p \leq 0.05$. Values are the mean ± S.E. from 5 replicates.

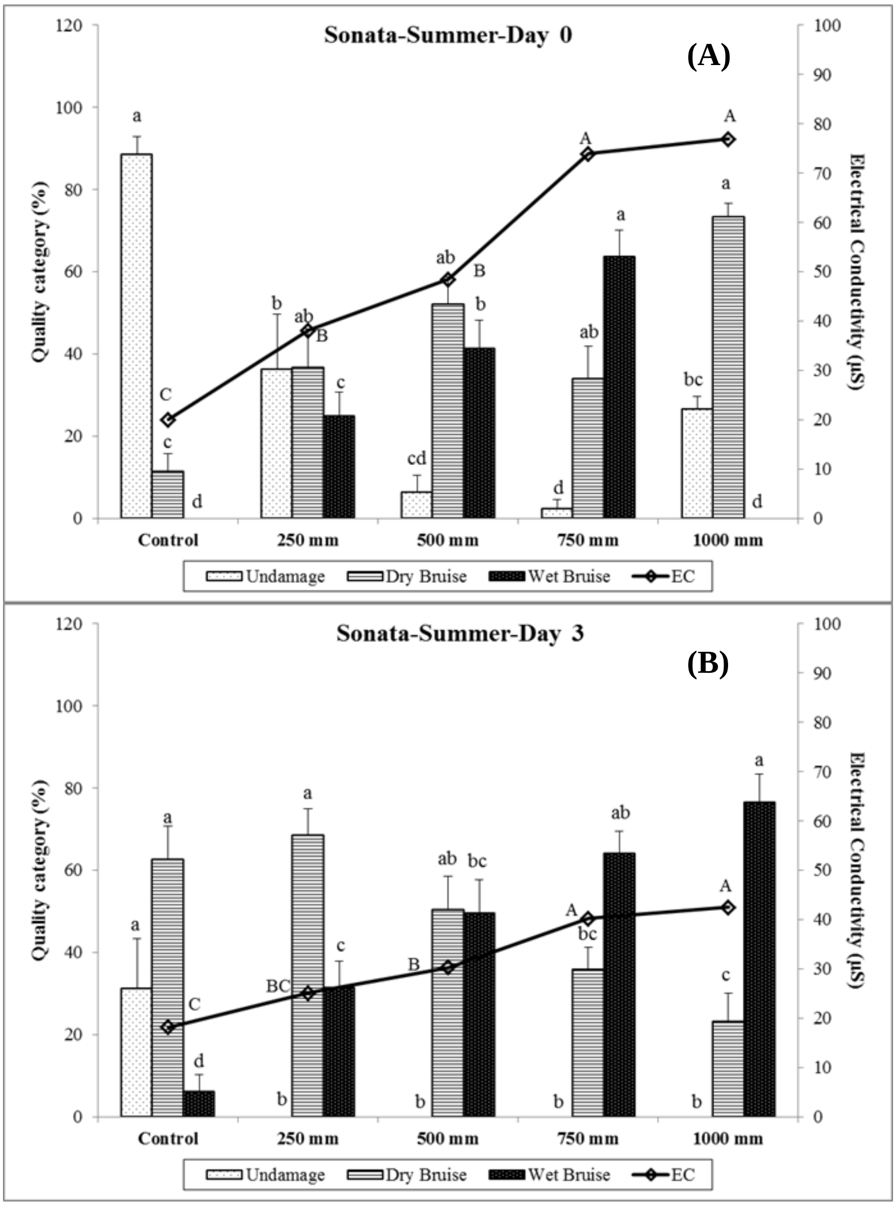


Figure 4.10: Effect of impact test on quality category and electrical conductivity of 'Sonata' strawberries from the summer cultivation at day 0 (A) and day 3 (B). Different letters in the different heights for DMRT test indicate significant differences at p≤0.05. Values are the mean ±S.E. from 4 replicates.

4.5.3.2 Fruit weight, firmness (puncture and compression) and severity score of 'Sonata' strawberries after impact test

Table 4.3 shows that the average fruit size in 'Sonata' cultivar was nearly 20 g per fruit from both productions. There was no effect from the impact test on the fruit weight from the winter and summer productions. The result of fruit weight in 'Sonata' cultivar confirmed and agreed with the previous result in 'Elsanta' cultivar (Table 4.1).

A rise of drop height significantly decreased 'Sonata' fruit firmness in both productions by puncture and compression tests ($p \leq 0.05$). On the initial day (day 0) and the end of storage (day 2), the punnet dropped from 1000 mm gave the minimum fruit firmness, whereas control (no drop) had the maximum fruit firmness from the winter and summer cultivations ($p \leq 0.05$). The lowest firmness related to the minimum bruise score, with a score below 2 (severely damaged fruit) (Table 4.3).

4.5.3.3 TSS (%), TA (%) and TSS:TA ratio of 'Sonata' strawberries after impact test

Figures 4.11 and 4.12 show the result obtained from the analysis of TSS, TA and TSS:TA ratio of 'Sonata' strawberries. On the first day and at the end of storage, there were no significant differences in TSS, TA and TSS:TA ratio among the five height levels. These results match those observed in 'Elsanta' cultivar (Figures 4.4 and 4.5). In the winter cultivation, TSS and TA contents of 'Sonata' cultivar were nearly 8.5% and 0.9%, respectively (Figure 4.11), which was a similar level of TSS, but lower TA content, when compared to the summer cultivation (Figure 4.12). In the summer production, TSS content of 'Sonata' cultivar (8.5% TSS) was higher than that of 'Elsanta' cultivar (7.5% TSS) (Figures 4.5 and 4.12).

4.5.3.4 Fruit surface colour (L*, a*, b*, h*, and C* values) of 'Sonata' strawberries after impact test

As shown in Figure 4.13, an increase of drop height significantly affected the values of all colour attributes (L*, a*, b*, h*, and C* values) ($p \leq 0.05$). Control treatment (no drop) had significantly higher values (L*, a* and b*) on the first day and after low temperature storage ($p \leq 0.05$). The punnets dropped from a height of 1000 mm showed the lowest values (L*, a*, b* and C*), which agreed with the result of fruit surface colour in 'Elsanta' cultivar (Figure 4.6).

Table 4.3: Effect of impact test on fruit weight, firmness and severity score of 'Sonata' strawberries from the winter and summer cultivations at day 0 and day 3.

Height (mm)	Weight (g)	Puncture (kg)	Compression (kg)	Severity score
Day 0-Winter		***Sonata-Winter***		
Control	21.35±0.28	0.483^{a}±0.013	1.737^{a}±0.089	4.9^{a}±0.08
250 (0.613 J)	20.39±0.38	0.368^{b}±0.016	1.529^{ab}±0.091	4.0^{b}±0.09
500 (1.226 J)	20.63±1.20	0.347^{b}±0.022	1.368^{bc}±0.093	3.2^{c}±0.19
750 (1.839 J)	21.30±0.56	0.373^{b}±0.018	1.334^{bc}±0.045	2.2^{d}±0.17
1000 (2.453 J)	19.99±0.99	0.323^{b}±0.025	1.191^{c}±0.066	1.8^{e}±0.17
Day 3-Winter				
Control	19.47±0.59	0.542^{a}±0.139	1.696^{a}±0.047	4.1^{a}±0.15
250 (0.613 J)	18.65±1.38	0.525^{a}±0.040	1.451^{ab}±0.047	3.2^{b}±0.25
500 (1.226 J)	21.35±0.68	0.438^{b}±0.037	1.451^{ab}±0.074	2.8^{b}±0.04
750 (1.839 J)	19.91±0.69	0.418^{bc}±0.014	1.453^{ab}±0.094	2.2^{c}±0.13
1000 (2.453 J)	19.84±1.20	0.334^{c}±0.017	1.252^{b}±0.134	1.6^{d}±0.06
Day 0-Summer		***Sonata-Summer***		
Control	20.40±0.28	0.426^{a}±0.025	1.786^{a}±0.087	4.9^{a}±0.03
250 (0.613 J)	21.90±0.38	0.408^{a}±0.043	1.778^{a}±0.044	4.3^{b}±0.16
500 (1.226 J)	21.42±1.20	0.377^{a}±0.013	1.543^{b}±0.044	3.8^{c}±0.05
750 (1.839 J)	22.33±0.56	0.376^{a}±0.008	1.363^{b}±0.048	3.2^{d}±0.06
1000 (2.453 J)	20.44±0.99	0.299^{b}±0.019	1.428^{b}±0.079	2.7^{e}±0.17
Day 3-Summer				
Control	18.51±1.32	0.516^{a}±0.017	1.899^{a}±0.093	4.5^{a}±0.15
250 (0.613 J)	18.04±1.83	0.467^{ab}±0.031	1.731^{ab}±0.057	3.6^{b}±0.06
500 (1.226 J)	18.22±1.96	0.410^{bc}±0.029	1.671^{bc}±0.077	3.2^{bc}±0.10
750 (1.839 J)	20.60±1.11	0.387^{c}±0.000	1.630^{bc}±0.042	2.9^{c}±0.13
1000 (2.453 J)	19.78±0.95	0.374^{c}±0.014	1.492^{c}±0.050	2.3^{d}±0.21

Means with different letters in the same column at each day are significantly different at $p \leq 0.05$. Values are the mean ±S.E. from 5 replicates (winter) and 4 replicates (summer).

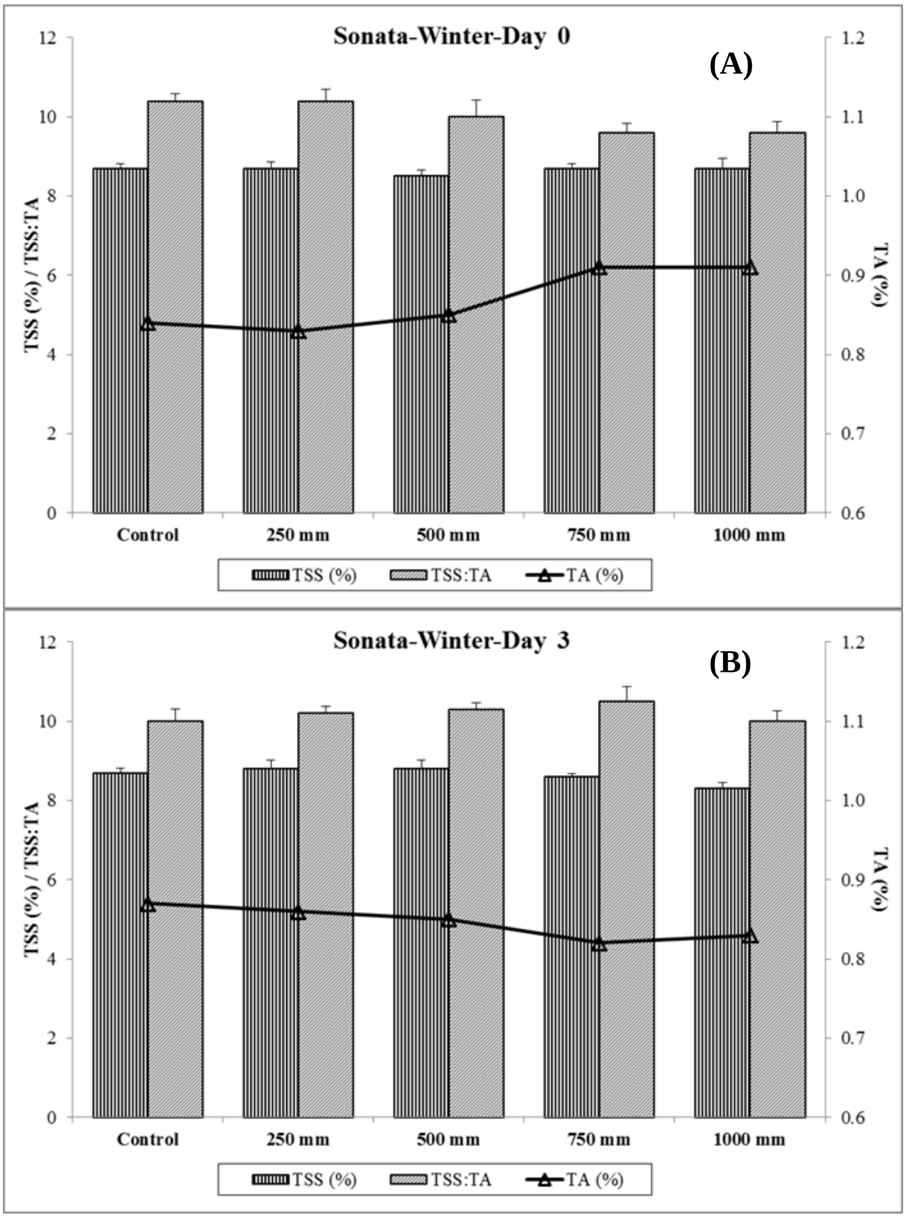


Figure 4.11: Effect of impact test on TSS (%), TA (%) and TSS:TA ratio contents of 'Sonata' strawberries from the winter cultivation at day 0 (A) and day 3 (B). Different letters in the different heights for DMRT test indicate significant differences at $p \leq 0.05$. Values are the mean ±S.E. from 5 replicates

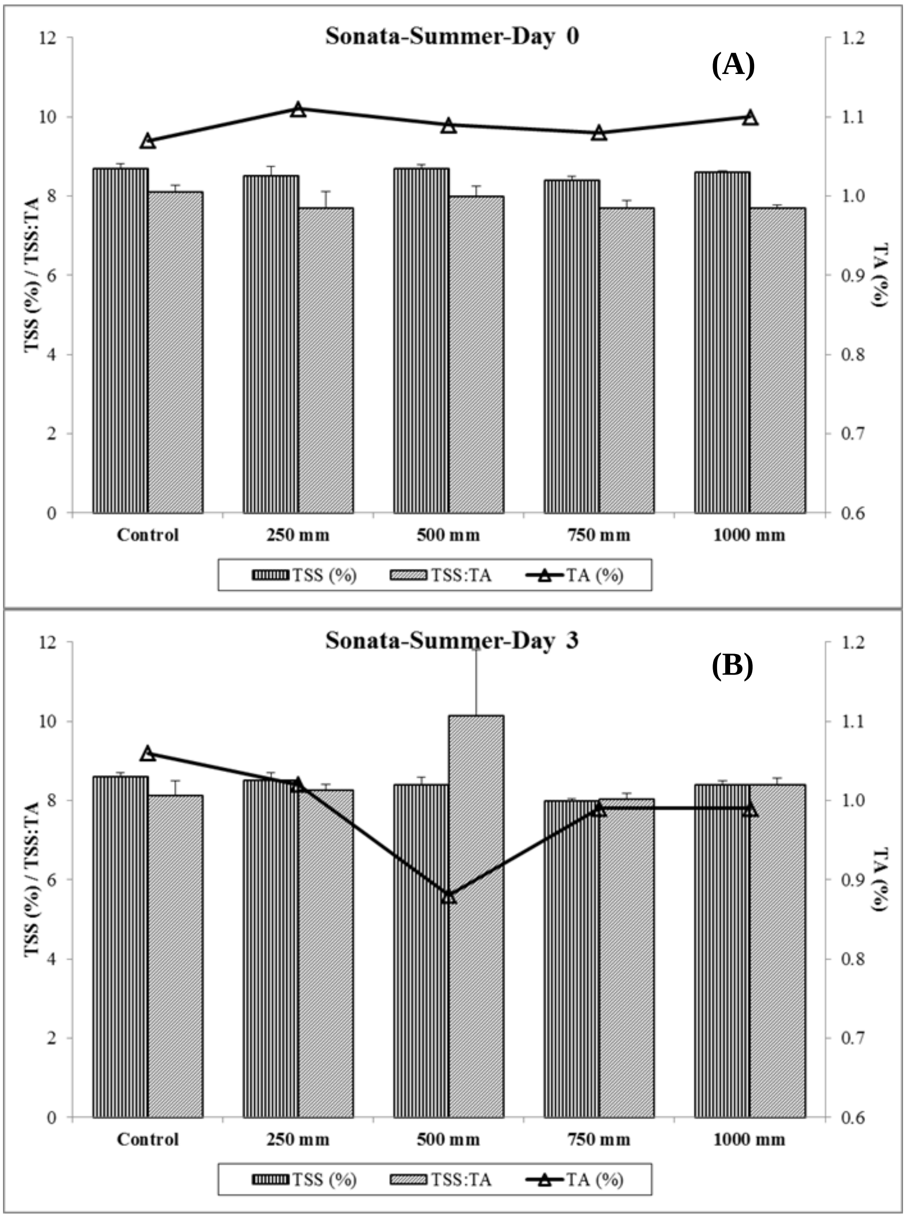


Figure 4.12: Effect of impact test on TSS (%), TA (%) and TSS:TA ratio contents of 'Sonata' strawberries from the summer cultivation at day 0 (A) and day 3 (B). Different letters in the different heights for DMRT test indicate significant differences at $p \leq 0.05$. Values are the mean ±S.E. from 4 replicates.

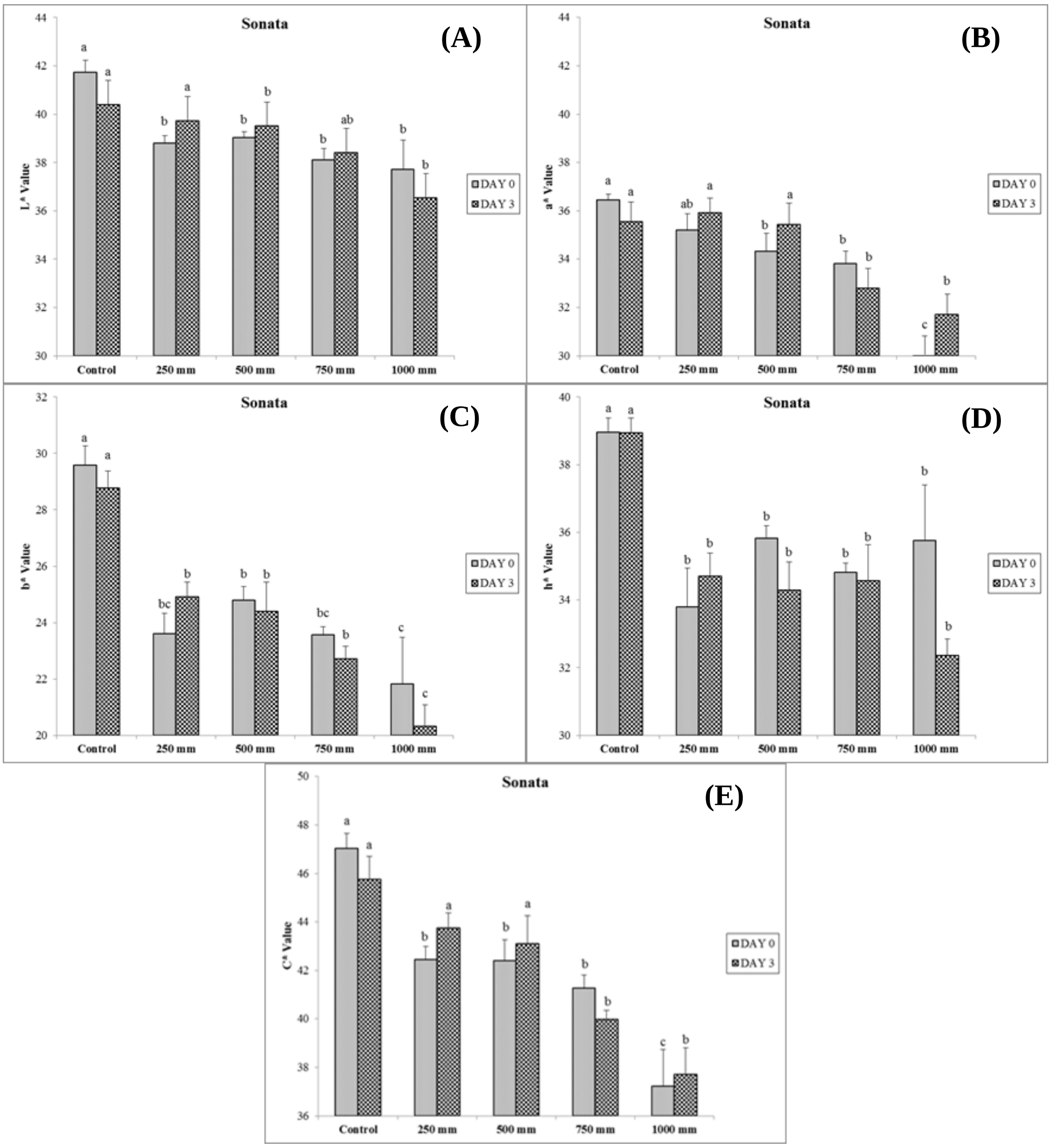


Figure 4.13: Effect of impact test on the values of L* (A), a* (B), b* (C), h* (D) and C* (E) of 'Sonata' strawberries from the summer cultivation at day 0 and day 3. Different letters in the different heights for DMRT test indicate significant differences at p≤0.05. Values are the mean ±S.E. from 4 replicates.

4.5.3.5 Weight loss (%) after storage of 'Sonata' strawberries after impact test

The punnet dropped from the height levels of 0 to 1000 mm was not significantly different in the percentage of weight loss ($p \leq 0.05$). Weight loss of 'Sonata' strawberries gradually increased over the entire storage period, which gave a higher weight loss in winter (approximate 2.5%) than in summer (approximate 1.5%) (Table 4.4). These results agree with the weight loss results of 'Elsanta' strawberries (Table 4.2).

Table 4.4: Effect of impact test on weight loss (%) of 'Sonata' strawberries from the winter and summer cultivations during storage at10^{o}C for 3 days.

	Weight loss (%) (Sonata)		
Height (mm)	**Day 1**	**Day 2**	**Day 3**
Winter			
Control	0.82±0.12	1.51±0.15	1.90±0.29
250 (0.613 J)	1.04±0.07	1.91±0.07	2.64±0.16
500 (1.226 J)	1.09±0.08	1.84±0.10	2.59±0.16
750 (1.839 J)	0.94±0.08	1.69±0.10	2.43±0.14
1000 (2.453 J)	0.88±0.05	1.65±0.09	2.39±0.16
Summer			
Control	0.65±0.08	1.00±0.09	1.33±0.09
250 (0.613 J)	0.88±0.05	1.22±0.05	1.45±0.07
500 (1.226 J)	0.74±0.12	1.16±0.07	1.44±0.07
750 (1.839 J)	0.77±0.07	1.18±0.04	1.39±0.06
1000 (2.453 J)	0.57±0.11	0.93±0.08	1.18±0.07

Means with different letters in the same column at each season are significantly different at $p \leq 0.05$. Values are the mean ±S.E. from 5 replicates (winter) and 4 replicates (summer).

4.5.3.6 Respiration rate, percentage of quality category and severity score of 'Sonata' strawberries after impact test

The respiration rate results of 'Sonata' after impact test are shown in Figures 4.14A-B. The respiration rates of all treatments in the winter production (35.85-48.87 mgCO_2/kg.hr) were lower than those in the summer production (46.97-69.74 mgCO_2/kg.hr). Immediately after the vibration test (0 hour), the highest respiration rates of 'Sonata' fruits from the winter cultivation were found in the height levels of over 500 mm approximate 50 mgCO_2/kg.hr (Figure 4.14A). In the summer cultivation, the punnets dropped from the height levels of 750 and 1000 mm had the greatest respiration rate of 'Sonata' strawberries approximately 70 mgCO_2/kg.hr (Figure 4.14B). The respiration rate of 'Sonata' strawberries gradually declined within 24 hours in a similar fashion as for the respiration rate in 'Elsanta' strawberries. After storage at 10^{o}C for 96 hours, the respiration rates of all height levels from both seasons were approximately 30-40 mgCO_2/kg.hr, which were lower than those respiration rates of 'Elsanta strawberries (Figures 4.7A-B and 4.14A-B).

The severity score of bruise was evaluated after storage at low temperature for 96 hours. Control treatment had the highest percentage of undamaged fruits (80%) (Figures 4.15A-B). The strawberry fruits from the summer production in 2014 were observed mould incidence (20-40%), whereas there was no mould incidence in the winter production in 2015. The greatest wet bruise was found in the height levels of 1000 mm ($p \leq 0.05$) (Figure 4.15A). The severity score from the height levels (500 to 1000 mm) (winter season) gave a score below 3, while only the control treatment (summer season) shows a score over 3 (Figures 4.15A-B).

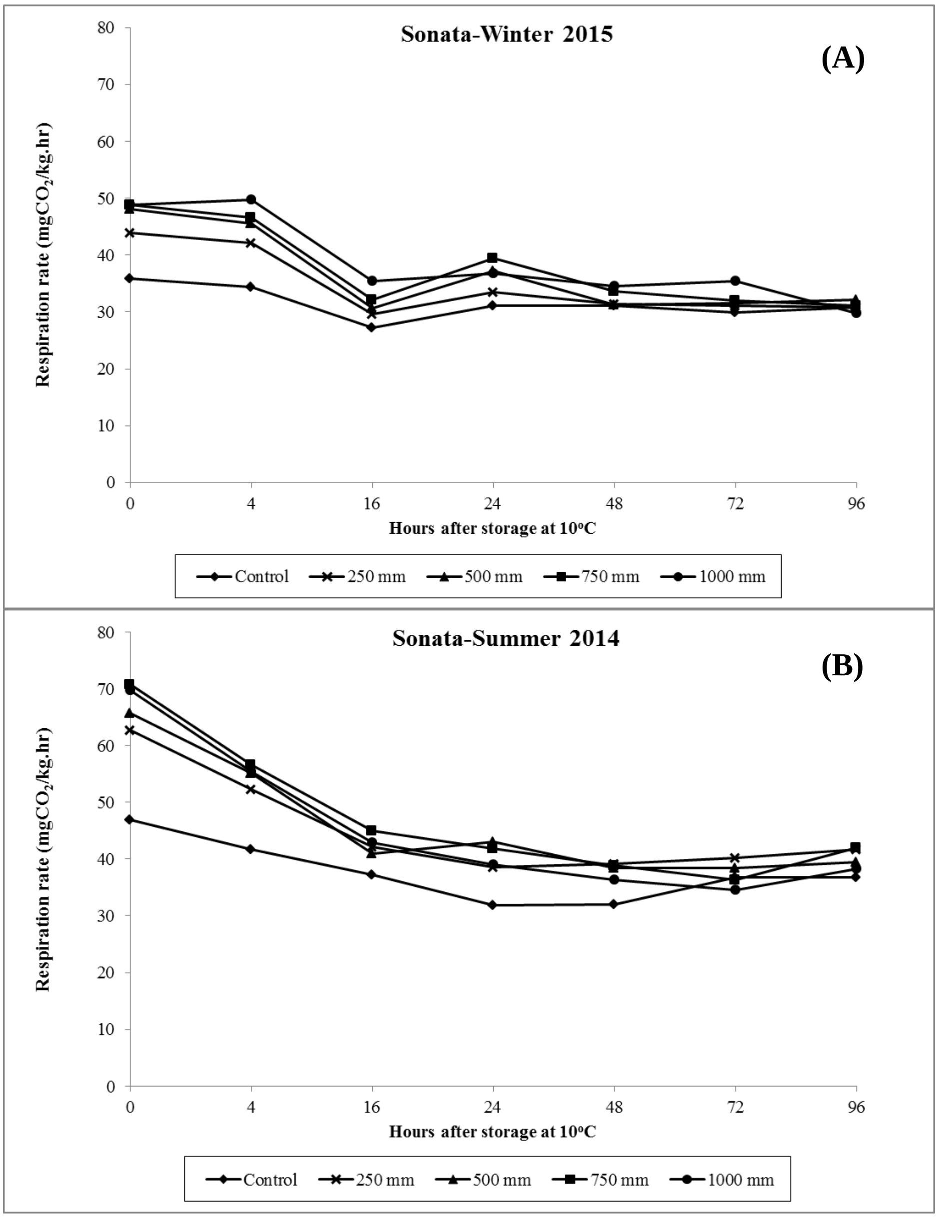


Figure 4.14: Effect of impact test on the respiration rate of 'Sonata' strawberries from the winter cultivation in 2015 (A) and the summer cultivation in 2014 (B) after storage at 10^{o}C for between 0-96 hours. Values are the mean from 5 replicates (winter) and 3 replicates (summer). The S.E. values of treatments with a range of ± 2.44 (winter) and ± 4.53 (summer) values were not shown due to the overlap in error bars producing a confusing graph.

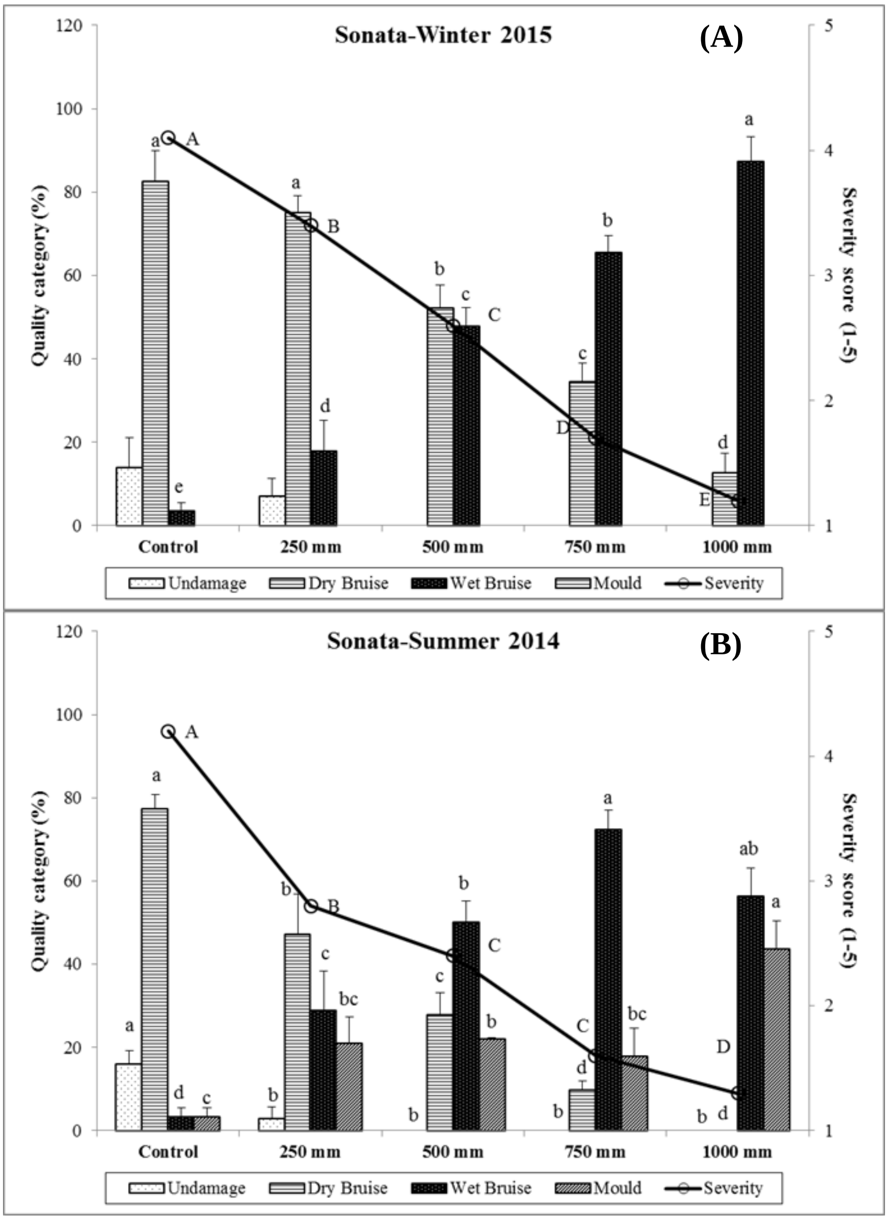


Figure 4.15: Effect of impact test on quality category and severity bruise score of 'Sonata' strawberries from the winter cultivation in 2015 (A) and the summer cultivation in 2014 (B) after storage at 10°C for 96 hours. Different letters in the different heights for DMRT test indicate significant differences at p≤0.05. Values are the mean ±S.E. from 5 replicates (winter) and 3 replicates (summer).

4.5.4 Correlation coefficient (r) between EC value or firmness, and fruit bruise in 'Elsanta' and 'Sonata' strawberry cultivars after impact test

From the five height levels of impact test and storage (day 0 and day 3), all fruit samples were analysed by Pearson's correlation at $p \leq 0.01$. The data analysis of correlation coefficient (*r*) between the four selected methods and strawberry bruise was analysed for each cultivar, storage time and cultivation as shown in Tables 4.5- 4.7. The selected four objective methods were EC, puncture, compression and respiration rate, which were analysed for correlation between bruise parameters (dry bruise, wet bruise and severity score). The results of these correlation values indicate which technique is suggested as a potentially most useful method of bruise assessment. Also, the correlation analysis between the four objective methods on day 0 (immediately after drop test) and bruise damages of strawberries on day 3 (storage at 10^{o}C) shows a predictor to determine impact damage.

4.5.4.1 The correlation between physical properties (EC, firmness, and respiration rate) and fruit bruise of 'Elasata' strawberries after impact test and storage

The results of the correlation analysis in 'Elsanta' strawberries on day 0 and day 3 from both cultivations can be compared in Table 4.5. In the winter and summer cultivations, the fruit damage from wet bruise on day 0 and day 3 gave a significantly higher correlation than from dry bruise ($p \leq 0.01$). Additionally, the correlation coefficient values between the EC method and wet bruise of fruits were higher than with puncture test, compression test and respiration rate, respectively ($p \leq 0.01$). The puncture test gave a higher relationship of that fruit damage and severity than the compression test, and appears to be the most effective for impact test. Therefore, the EC method correlated to the fruit damage from wet bruise and severity score after impact test (day 0) and after storage condition (day 3) when compared with other three objective methods ($p \leq 0.01$).

4.5.4.2 The correlation between physical properties (EC, firmness, and respiration rate) and fruit bruise of 'Sonata' strawberries after impact test and storage

As can be seen from Table 4.6 (Sonata cultivar), the correlation coefficient (*r*) between the four selected methods and wet bruise showed a significantly greater relationship than with dry bruise for the winter cultivation ($p \leq 0.01$). The EC method still gave a greater relationship with wet bruise and severity score on day 0 and day 3 than firmness tests and respiration rate ($p \leq 0.01$). These results agreed with those correlation results for 'Elsanta cultivar (Table 4.5). However, for the summer cultivation on day 0, the EC, puncture and compression determinations for wet bruise fruits had a lower correlation coefficient level than the winter cultivation on day 0.

Table 4.5: The correlation coefficient (*r*) between bruise determinations (EC, firmness and respiration rate values) and fruit bruise of 'Elsanta' strawberries on day 0 and day 3.

Properties	Dry bruise	Wet bruise	Severity score	Dry bruise	Wet bruise	Severity score
		Elsanta-Winter cultivation Day 0			***Elsanta-Summer cultivation Day 0***	
EC	0.491	0.884**	-0.894**	0.022	0.876**	-0.863**
Puncture	-0.619**	-0.781**	0.845**	0.069	-0.640**	0.683**
Compression	-0.383	-0.749**	0.779**	-0.398	-0.227	0.397
Respiration rate	0.534**	0.556**	-0.600**	0.436	0.538	-0.642**
		Elsanta-Winter cultivation Day 3			***Elsanta-Summer cultivation Day 3***	
EC	-0.424	0.860**	-0.899**	-0.876**	0.913**	-0.699**
Puncture	0.283	-0.780**	0.914**	-0.698**	-0.741**	0.629**
Compression	0.478	-0.841**	0.797**	0.340	-0.382	0.425
Respiration rate	-0.019	0.103	-0.042	-0.004	0.076	0.092

** Pearson's correlation is significant at 1% level in the winter cultivation on day 0 or day 3 (n=25) and the summer cultivation day 0 or day 3 (n=20).

Table 4.6: The correlation coefficient (*r*) between bruise determinations (EC, firmness and respiration rate values) and fruit bruise of 'Sonata' strawberries on day 0 and day 3.

Properties	**Dry bruise**	**Wet bruise**	**Severity score**	**Dry bruise**	**Wet bruise**	**Severity score**
	Sonata-Winter cultivation			***Sonata-Summer cultivation***		
	Day 0			***Day 0***		
EC	0.519**	0.771**	-0.869**	0.501	0.343	-0.899**
Puncture	-0.548**	-0.645**	-0.730**	0.663**	-0.002	0.728**
Compression	-0.440	-0.676**	0.731**	-0.501	-0.393	0.813**
Respiration rate	0.665**	0.499	-0.691**	0.575	0.424	-0.737**
	Sonata-Winter cultivation			***Sonata-Summer cultivation***		
	Day 3			***Day 3***		
EC	-0.619**	0.857**	-0.898**	-0.698**	0.836**	-0.839**
Puncture	0.661**	-0.790**	0.687**	0.460	-0.714**	0.757**
Compression	0.307	-0.524**	0.584**	0.523	-0.750**	0.781**
Respiration rate	-0.225	0.338	-0.372	0.261	-0.164	0.219

** Pearson's correlation is significant at 1% level in the winter cultivation on day 0 or day 3 (n=25) and the summer cultivation day 0 or day 3 (n=20).

4.5.4.3 The correlation between physical properties (EC, firmness, and respiration rate) immediately after impact test on day 0 and fruit bruise of 'Elsanta' and 'Sonata' strawberries and after storage on day 3

According to the 'Elsanta' and 'Sonata' results of correlation, overall, the EC method gave the greatest consistency as a bruise indicator for measurements of wet bruise and severity score when compared with the firmness tests and respiration rate measurement (Tables 4.5 and 4.6). As shown in Table 4.7, after impact test on day 0, the EC method also gave a significantly greater linear correlation than the other three objective methods for the bruise assessment of 'Elsanta' and 'Sonata' strawberries on day 3 ($p \leq 0.01$). These correlation results indicated that the EC values from day 0 could give a prediction of the wet bruise incidence and severity score of both cultivars and cultivations after storage at 10^{o}C for 3 days. In this impact study, therefore, the EC method is suggested to be used to determine the impact damage of strawberry fruits from wet bruise and to use as the bruise indicator and predictor of strawberries after immediately impact test and cool storage for 3 days.

Table 4.7: The correlation coefficient (*r*) between bruise determinations (EC, firmness and respiration rate values) on day 0 and fruit bruise of 'Elsanta' and 'Sonata' strawberries on day 3 after storage.

Properties (Day 0)	**Dry bruise**	**Wet bruise**	**Severity score**	**Dry bruise**	**Wet bruise**	**Severity score**
	Elsanta-Winter cultivation Day 3			***Elsanta-Summer cultivation Day 3***		
EC	-0.331	0.834**	-0.887**	-0.811**	0.874**	-0.750**
Puncture	-0.003	-0.697**	0.847**	0.615**	-0.654**	0.490
Compression	0.461	-0.751**	-0.759**	0.271	0.334	0.497
Respiration rate	0.037	0.500	-0.655**	-0.585	0.694**	-0.676**
	Sonata-Winter cultivation Day 3			***Sonata-Summer cultivation Day 3***		
EC	-0.470	0.815**	-0.882**	-0.699**	0.833**	-0.855**
Puncture	0.319	-0.672**	0.736**	0.317	-0.530	0.651**
Compression	0.324	-0.625**	0.733**	0.554*	-0.623**	0.696**
Respiration rate	-0.178	0.537**	-0.662**	-0.395	0.659**	-0.672**

** Pearson's correlation is significant at 1% level in the winter cultivation (n=25) and and the summer cultivation (n=20).

4.6 DISCUSSION

4.6.1 The effect of temperature in the greenhouse on the reproductive growth and quality of ‘Elsanta’ and ‘Sonata’ strawberries

4.6.1.1 Fruit size and yield

Without the controlling temperature system, ‘Elsanta’ and ‘Sonata’ strawberry plants were grown in the greenhouse during the winter (2014 and 2015) and summer (2014) seasons. Solar radiation contributed to the greenhouse during the day, particularly providing maximum temperature over 40^{o}C at 12.00 h of each month. Consequently, the temperature dropped in the night to the lowest temperatur below 2^{o}C in the winter cultivation, while the lowest temperature of each month in the summer cultivation was around 10^{o}C. The temperature inside the greenhouse of this study affected the period of cultivation, fruit size and yield as well as fruit quality.

The period of the winter cultivation in 2014 and 2015 was 72-75 days, which was a longer period than for the summer season of 36 days. The range of average temperatures during the summer cultivation in 2014 (21 to 25^{o}C) was higher than that of the winter cultivations in 2014 and 2015 (8 to 21^{o}C) (Table 3.2). A higher temperature during the summer cultivation gave a reduced fruit weight (Tables 4.1, 5.1, 5.2, 5.4 and 5.5) and yield (data not shown), which gave fewer fruits for replications for both impact and vibration tests. Ledesma *et al.* (2008) reported a negative effect of high temperature stress on the reproductive process in ‘Nyoho’ and ‘Toyonka’ strawberries such as the number of inflorescences, flowers and fruits. Singh *et al.* (2007a) found that later plantings produced the development of smaller fruit, lower yield, and shorter fruiting period due to an increased temperature. Additionally, higher temperature on the fruit surface enhanced the ripening process and reduced the crop cycle duration (Palencia *et al.*, 2013). These results are consistent with the findings of Ledesma *et al.* (2008), who found that the number of days to ripening at a higher temperature was also less than at a lower temperature.

There has been little a relationship between irrigation water with fruit size and quality in greenhouse production. The fertigation system with a single drip line was used in this current study. The period of irrigation water in the summer cultivation was applied 3-4 times per day, which was a higher water use than the winter cultivation. Yuan *et al.* (2004) reported that an increasing amount of irrigation water by drip irrigation increased fruit size and fruit yield of 'Schinoka' strawberry inside plastic greenhouse. In contrast, the findings of the current study differ from the previous study. It is possible therefore that a higher temperature in the greenhouse is a major preharvest factor in a reduction of fruit size and fruit yield.

4.6.1.2 Fruit firmness, EC value and contents of TSS and TA

Seasonal and cultural variations are further potential confounding factors for comparison or inclusion for studies of different growing seasons and sites (Knee and Miller, 2002). Summer strawberry production led to a reduction of fruit firmness in both puncture and compression values (Tables 4.1, 5.4 and 5.5). Another study gave a significant negative correlation between strawberry fruit firmness and growing temperature (r = -0.87) (Pyrotis *et al*., 2012). In the current study before impact and vibration tests, the undamaged fruits from the summer cultivation of control (no treatment) showed a higher fruit softening than those fruits from the winter cultivation. Also, the incidence of bruising in the fruits for the summer cultivation was found to be around 20% of total fruits before testing due to the effect of the high temperature in the greenhouse during summer cultivation (Figures 4.3, 4.10 5.4 and 5.19) (Table 3.2). The EC value of the summer fruits (undamaged fruits) increased by 10 µS as compared to those fruits from the winter cultivation which negatively related to a reduction of fruit firmness. Moreover, after impact and vibration tests, the percentage of undamaged fruits and wet bruise from both strawberry cultivars increased in the summer cultivation in 2014 when compared with the winter cultivations in 2014 and 2015 (Figures 4.2- 4.3, 4.19-4.20, 5.2-5.5 and 5.15-5.20). Therefore, the higher average temperature of 21 to 25^{o}C during the summer cultivation caused the increase of fruit softening, EC value and strawberry bruise before and after impact and vibration tests.

The chemical compositions of berry fruits depend on cultivar, growing site, maturity and storage condition (Talcott, 2007). For a good flavour, strawberry fruits should contain high sugar and acid contents (Mitcham, 1996). The average contents of TSS, TA contents in 'Elsanta' and 'Sonata' cultivars were at similar levels, which were around 8%TSS and 1.0%TA levels. The results of this trial agreed with these levels from the winter cultivation in Eastern Austria, where the TSS and TA contents of 'Elsanta' and 'Sonata' were 9.9% and 9.19%TSS, and 1.1% and 0.96%TA, respectively (Spornberger *et al.*, 2008).

In the current study, the seasonal cultivation notably affected TSS and TA contents. The low temperature during the winter cultivation (May harvesting) also produced strawberry fruits which contained higher TSS and lower TA contents. In the summer production, these strawberries contained a lower TSS with 7.5-8% (Figures 4.4-4.5, 4.11-4.14, 5.6-5.9 and 5.21-5.24); however, this still was an acceptable flavour for strawberries at 7% (TSS) as reported by Kader (1999). Literature data shows that a lower temperature during strawberry fruit development through to winter season led to higher sugar contents such as glucose, fructose and sucrose (Ferreya *et al.*, 2007). Singh *et al.* (2007) also reported that early planting produced a significantly higher TSS content than later planting. The unfavourable environment at high temperature environment enhanced fruit development. Rahman *et al.* (2014) confirmed that the strawberries from the early cultivation (September) contained more TSS content than late cultivation (December) due to favourable conditions and a longer time for sugar accumulation in the early cultivation.

In the current study, therefore, the season cultivation directly affected the preharvest quality of strawberries such as fruit size, yield, bruised fruit, fruit firmness, and EC value, as well as the contents of TSS and TA. Initially, all of the above-mentioned quantity and quality attributes in the winter cultivation were better than in the summer cultivation due to greater fruit size, yield, fruit texture and TSS content, including less bruise damage.

4.6.2 The effect of impact test on the quality, bruise and respiration rate of 'Elsanta' and 'Sonata' strawberries

4.6.2.1 Bruise damage from impact test

Impact damage is the most severe mechanical injury in fruit handling (Van Zebroeck *et al.*, 2007a). The impact test by a fixed mass dropped onto a surface may be more representative of what occurs in fruits after harvesting (Knee and Miller, 2002). There has been little published research for impact test on the strawberry punnet. For previous tests of an individual berry fruit, a wide range of drop heights was used, from 50 to 1200 mm on the different surface materials (Ferreira *et al.*; 2008, Kitazawa *et al.*; 2014; Yu *et al.*, 2014). The metal or steel material provided the highest impact bruise in kiwifruit (Mencarelli *et al.*, 1996), peach (Reza, 2013), tomato (Idah *et al.*, 2007) and table olive fruits (Saracoglu *et al.,* 2011). In this impact study, therefore, the simulated impact test was conducted by a drop test from 0 to 1000 mm onto a mild metal sheet as this was expected to cause the highest bruise severity.

Important quality characteristics of strawberries are being free from defects, juice leakage, and sponginess (Mitcham 1996; Ṕeneau *et al.*, 2007). In this impact experiment, immediately after impact test from a specific height for five consecutive drops, the percentage of undamaged fruits at the lowest height (250 mm) with the minimum impact energy (0.613 J) was significantly reduced by approximately 60% when compared to no drop fruits (Figures 4.2A-4.3A and 4.9A-4.10A). As a consideration of height level in strawberry handling, the drop height of 250-1000 is a possibility to give impact bruise, which is an agreement with an apple postharvest handling study, the potential drop heights at farm were 600 mm, which was higher than a drop height of 50-300 mm at the retailer on display (Lewis *et al.*, 2008).

The cushion by a bubble sheet is commonly inserted within a punnet for damage protection of strawberries (Terry, 2012). In this impact test, a bubble sheet as cushion did not greatly protect strawberries from bruise damage, even at the lowest height of 250 mm (0.613 J). At a drop height of 1000 mm with the maximum impact energy (2.153 J), the percentage of wet bruise notably increased, while height levels of 0, 250 and 500 mm (1.226 J) did not give a significant difference in dry bruise (day 3) (Figures 4.3B, 4.9B and 4.10B). Higher impact energy and energy absorbed were associated with an increase of drop height and fruit mass (Jiménez-Jiménez *et al,* 2013). In this impact study, the fruit uniformity was selected at approximately 20 g per fruit, except ‘Elsanta’ cultivar (14 g per fruit) in the summer cultivation as the weight of the packed strawberry punnet was 250±10 g. Thus, the impact energy and energy absorbed should relate to the drop height. Moreover, an increasing number of drops also related to a reduction of impact energy, which was reported by Gołacki *et al.* (2009). The first drop of an apple gave higher impact energy when compared to the fourth or fifth drop. In this impact study, the maximum height that will not produce damage with severity score over 3, for five consecutive drops onto a hard surface material. In addition, further research should be done to examine the effect of the impact test on another surface material: such as corrugated fibreboard and hard plastic, including a study in multiple impact tests for strawberry punnets.

After storage at 10^{o}C for 3 days, the overall degree of dry bruise increased and there was not a significant difference in heights of 0, 250 and 500 mm (Figures 4.3B, 4.9B and 4.10B). Moreover, the bruised strawberries resulted from impact stress by a punnet dropping from a specific height. It is possible that the greater bruise damage of strawberries results from various causes such as compression stress, fruit-to-fruit impact, impact contact time, energy absorbed, storage temperature and turgor pressure. Holt and Schoorl (1982) also stated that a slow compression stress on strawberries gave more bruising than impact damage. Compression led to a change of the cell dimension by cell wall fracture. Also, another impact damage was fruit-to-fruit, which was reported in apple-to-apple research. A total bruising volume of both fruits (fruit-to-fruit) correlated to the energy absorbed in apples, whereas the bruise fruits have generally been more severe on one of the two fruits (Pang *et al.*, 1992). In this impact study, a simulated storage condition at 10^{o}C for 3 days led to more bruise damage. The cool temperature was at 3-17^{o}C on the strawberry displays in supermarkets (Russell *et al.*, 2009; Nunes *et al.*, 2009; Chaiwong and Bishop, 2015). It is possible that higher bruise damage may cause an increase in impact contact time (Brusewitz and Bartsch, 1989) or a higher absorbed energy at a higher storage temperature (Ahmadi *et al.*, 2010; Ahmadi, 2012). Shafie *et al.* (2015) reported that the bruise volume of pomegranate increased throughout storage time and temperature due to a reduction of turgor pressure. Thus, further research might investigate additional factors to strawberry bruising such as compression force and fruit-to-fruit impact.

4.6.2.2 Severity score, fruit shape and mould incidence

Commercially, a bruise determination of the percentage bruise area is more important than bruise volume (Pang *et al.*, 1992). A bruise determination of strawberries is based on the bruise area and is converted to severity score (Figure 3.5). The wet bruise was observed in a score below 3 as the severity score of limited acceptability of strawberry quality (a score 3). On day 0, the maximum height of limited acceptability of 'Elsanta' and 'Sonata' cultivars was 750 mm (1.839 J), whereas the maximum height for those cultivars was 500 mm (1.226 J) after low temperature storage for 3 days (Tables 4.1 and 4.3). As expected, the severity score of bruised strawberries significantly related to firmness by puncture test (Table 4.1). Thus, a severity score based on the percentage of bruise area could be used as a method of evaluating bruises due to a good relationship with firmness and may be related to bruise volume. Ferrreira *et al.* (2008) reported that the largest bruise volume of 'Oso Grande' and 'Sweet Charlie' strawberries was from a height of 380 mm (0.075 J), which correlated to the impact energy. Also, an increase of bruise level was strongly correlated with impact energy and energy absorbed in banana (Kajuna *et al.*, 1997), apple (Schoorl and Holt, 1980; Pang *et al.*, 1992) and olive (Jiménez- Jiménez *et al*, 2013). The bruise volume of 'Redland Earlisweet' and 'Redlands Crimson' strawberries had a strong correlation with energy absorbed for impact and compression (Holt and Schoorl, 1982). It has commonly been assumed that determined severity score by the percentage of bruise area is associated with impact energy and energy absorbed.

The cause of bruise damage may be a failure of intercellular bonds or actual cleavage of the cells. A firmness change of bruised tomato related to polygalacturonase (PG) activity was reported by

Lee *et al.* (2007). The PGs activity and EC value of bruised tomato from a drop of 400 mm reduced during the first two days of storage at 20°C and increased following ripening after 6 days. In contrast, another report by Van linden *et al.* (2008) found no considerable changes in pactinmethylesterase (PME) and polygalacturonase (PG) activities, including no leading to a significant change in the absolute and relative amounts of pectin fractions. In the case of cell wall degradation in strawberries, Terry (2012) reported that there was not a fully established connection between strawberry softening and changes in polygalacturonase (PG) during ripening. Thus, the changes of the enzymatic system are still unclear to explain fruit softening in bruised fruit.

A number of studies have examined the effect of fruit shape on fruit damage from impact test, especially radius of curvature. A small radius of curvature caused more bruise than a large radius of curvature in apples (Zarifneshat *et al.*, 2010), peaches (Ahmadi *et al.*, 2010), kiwifruits (Ahmadi *et al.*, 2012) and tomatoes (Van Zeebroeck *et al*., 2007b). The elongated shape of olive fruit had a low bruise damage (Jiménez- Jiménez *et al.*, 2013). As shown in Appendix 3.1, the fruit shapes of two cultivars were evaluated by the maximum length, major lateral and minor later diameters for calculations such as fruit shape index, ellipsoid ratio and roundness. There were no significant differences in all these parameters, except a statistically significantly longer lateral diameter of 'Sonata' fruits by 2 mm. A tendency of the fruit shape index in 'Elsanta' fruit showed more of an oval shape than 'Sonata' fruit (round shape), that is, 'Sonata' fruit could have a small radius of curvature. However, the overall difference in bruise between two cultivars was not significant (data not shown). It seems possible that the fruit shape of strawberries may not affect bruise damage from impact test.

In this impact study, the storage condition at 10°C for 3 days controlled the mould incidence. However, after storage for 4 days, the mould incidence (overall average of 10-20%) was observed in the summer cultivation (2014), whereas there was no mould incidence in the winter cultivation (2015) (Figures 4.8 and 4.15). In the summer cultivation, a great number of smaller fruits (less than 10 g per fruits) were often not picked as they were of an unacceptable size for this study (data not shown). Non-picked fruits may increase levels of preharvest disease in the field (Terry *et al.*, 2011), whilst growers usually pick unsaleable fruits to prevent the build up of disease in the commercial harvesting of the strawberries in the UK. Furthermore, in this impact study, the tendency of fruit firmness in the summer cultivation was less than in the winter cultivation, particularly for the 'Elsanta' cultivar (Table 4.1). Non-picked fruit and softer fruit may cause strawberries to be susceptible to postharvest disease during low temperature storage at 10^{o}C.

4.6.2.3 Respiration rate, electrical conductivity (EC), fruit firmness and fruit weight

The evaluation of bruise by the physiological and biochemical methods was often restricted by them being time-consuming and destructive methods, and it was also difficult to apply mechanization and computerization (Knee and Miller, 2002). Furthermore, the bruise characteristics from impact, vibration and compression were a different pattern, which depended on fruits and fruit tissues (Chen *et al.*, 1987; Vergano *et al*., 1991; Underhill *et al.*, 1998); therefore, it was quite difficult to quantify the level of bruise (Underhill *et al.*, 1998). Nevertheless, the bruise area with high variation in bruise depths was not an appropriate index of total bruise volume in apple-to-apple (Studman *et al.* 1997). In this impact experiment, the drop height level of packed strawberries was indicated in physicochemical qualities and a severity score as well as the developing method to detect bruised strawberries.

The CO_2 evaluation of blueberries, sweet cherries and cranberries was suggested as an indicator of bruise damage by harvesting and handling operation (Burton and Schulte-Pason, 1987; Massey *et al.*, 1982). The maximum CO_2 production of impacted punnets occurred in the initial hour on day 0 and was notably higher than for intact fruits (Figures 4.7 and 4.14). This is in agreement with Lee *et al.* (2004, 2007) who studied the effect of impact test on respiration rate of Roma tomatoes. However, in the impact study, the respiration rate of strawberries might particularly be used as an indicator of bruise damage in only the winter cultivation due to distinguish between undamaged fruits and bruise damage fruits from a different height.

Electrical conductivity was a possible technique to evaluate strawberry bruising (Jiang *et al.*, 2001) and bruised bananas (Bugard *et al*., 2014). The EC method was recommended for damage evaluation of strawberries during postharvest handling and transport (Jiang *et al.*, 2001). Immediately after impact test (day 0), a higher height of drop test caused an increase in EC values of strawberry bruise. The EC value from the bruised strawberry in the summer cultivation increased twice as much as in the winter cultivation (Figures 4.2-4.3 and 4.9-4.10). A higher respiration rate from a higher drop height also correlated to an increased EC value, particularly in the summer cultivation (Figures 4.7B and 4.1B). After storage at 10^{o}C for 3 days, in this impact study, the EC values from bruised fruits declined (Figures 4.2B-4.3B and 4.11B-4.12B). Therefore, this finding supports previous research into the change of EC value in 'Tayonoka' strawberry bruise, which reduced after storage at 25^{o}C for 2 days (Jiang *et al.*, 2001).

In the current impact test, a gradual reduction of fruit firmness by puncture and compression tests significantly affected an increased drop height (Tables 4.1 and 4.3) as well as an increase of EC value (Figures 4.2-4.3 and 4.9-4.10). Also, the developing technique for bruise determination in strawberries was analysed for the correlation between EC or firmness method and bruise incidence. EC value had a significantly stronger correlation to wet bruise, rather than dry bruise. In fruit firmness tests for bruise evaluation, the puncture test with an 8 mm cylinder probe had a greater bruise correlation than the compression test with a 42 mm platen (Tables 4.5 and 4.6). The bruise incidence had a strong relation with fruit firmness such as with apples (Sinobas *et al.*, 1991) peaches (Hung and Prussia, 1989) and persimmons (Lee *et al.*, 2005). Furthermore, the fruit firmness depended on probe size and method of testing. The recommended probe size for a puncture test of strawberry was a diameter range of 4-8 mm (flat or blunt end) (Hietaranta and Linna, 1999; Mitcham *et al.*, 1996). Testoni *et al.* (1989) reported that a compression test was more reliable than a pressure test (puncture test) for evaluating susceptibility to rotting. This investigation of strawberry firmness has shown that the puncture test with an 8 mm cylinder probe is suggested to determine the firmness of bruised strawberries.

Accordingly, in the current impact study, the EC method gave the greatest correlation efficient value (*r*) to wet bruise and severity score, followed by the puncture test (Tables 4.5 and 4.6). Even though Salamat *et al.* (2013) reported conflicting results with that, there was a strong correlation between strawberry firmness (compression test) and bruise volume from a pendulum impactor test. In another piece of research on apple bruising from impact test, the bruise volume had a significantly weaker correlation with firmness (r = -0.20 to -0.45) (García *et al.*, 1995). Furthermore, Døving and Måge (2002) reported that with the Texture Analyser, they did not find any relationship between firmness and fruit weight. It is suggested that the relationship between fruit size and firmness relies on the cultivar and the testing method. As a current result, there was not a significant fruit weight (size) among the five levels of height so that strawberry bruise directly affected the firmness of strawberries (Table 4.3).

From the results of this investigation, the four objective methods (EC, puncture, compression respiration rate) were considered for bruise evaluation in strawberries from both cultivations on day 0 and day 3. In terms of developing non-destructive method, the respiration rate method could distinguish the differing CO_2 production among the different impact heights, but only for the winter cultivation. Also, this method required a longer period (7200 Sec) to determine bruise damage than the EC method (600 sec). The EC method represented the method with the best potential to determine after immediately impact test and cool storage for 3 days (r = 0.771 to 0.913) as well as severity score (Tables 4.5 and 4.6). The EC technique in this study also showed the best predictor of wet bruise incidence with different bruise level (severity score) after storage at 10^{o}C for 3 days (r > 0.750) (Table 4.7). In the future work, the EC method is suggested to be used for mathematical modelling with a simple linear regression to predict the impact bruise of strawberries from harvesting through display on the shelf in a retail store within 3 days. Also, the EC method is suggested to be an indicator of bruise damage due to being a non-destructive method and not complex and less time-consuming.

4.6.2.4 TSS, TA and TSS:TA contents, colour, and weight loss (%)

The impact test had no the effect on TSS, TA and TSS:TA contents of ‘Elsanta’and ‘Sonata’ cultivars from both cultivations (Figures 4.4-4.5 and 4.11-4.12). These results agree with the findings of Jeong *et al.* (2011) who found that the TSS content of strawberries was a small change during storage at 0^{o}C and 10^{o}C. Also, the contents of TA, TSS and TSS:TA contents of bruise tomato did not differ from control fruits (MacLeod *et al.*, 1976; Lee *et al.*, 2004, 2007). The TSS content of bruised blueberries was unaffected by impact test (Sanford *et al.*, 1991). Overall, bruise damage of strawberries did not affect strawberry flavour in terms of not changing TSS, TA and TSS:TA contents before and after low temperature storage.

A likely explanation is that these colour changes in bruised strawberries may result in an increase of anthocyanin content, EC value, storage period, temperature and weight loss as much as a reduction of firmness. In this study, all colour attributes of strawberry bruise were lower than for control samples. After storage at low temperature, the punnet dropped from 1000 mm had the lowest all these colour values (L*, a*, b*, h* and C*), while control treatment had the highest colour attributes (Figures 4.6 and 4.13). A reduction of lightness (L*) and hue angle (h*) values was observed in ‘Camino Real’ strawberries throughout at 5^{o}C and 15^{o}C (Pineli *et al.*, 2012). The bruising of lowbrush blueberries from a height of 1590 mm was a major colour change as measured by h* value from blue to blue-red, but was not associated with L* value. The colour changes in h* value of bruised blueberries may relate to the effect of cell breakdown on anthocyanin leakage from split blueberries (Sanford *et al*, 1991). Also, in this impact test, the bruised fruits from a drop height of 1000 mm also had significantly higher EC value and lower firmness than those for other height levels (Figures 4.2- 4.3 and 4.9-4.10) (Tables 4.1 and 4.3). In strawberry pulp, anthocyanin compounds (pelargonidin 3-rutinoside and pelargonidin 3-glucoside) were highly correlated with redness (a*) value of strawberry surface, followed by L* value of strawberry pulp during storage (Hernanz *et al.*, 2008). An increase in high temperature and storage time encouraged the accumulation of anthocyanin concentrations (Kalt *et al.*, 1993, 1999; Cordenunsi *et al.*, 2005). There is a possibility that a cool temperature of 10^{o}C for 3 days and anthocyanin leakage (high EC value) also may involve turning to a deep red due to an accumulation of anthocyanin content.

In the current study, the overall weight loss of both cultivars was approximately 2-3% throughout the entire storage (10°C and 70%RH) as much as a tendency of increased firmness. The impact damage in all these drop heights did not affect weight loss (Tables 4.2 and 4.4). The maximum acceptable weight loss (%) of strawberries was in the range of 2.5-3.0% after storage at 20°C for 2.5-3 days (Nunes and Emond, 2007). The influences of turgidity and firmness independently affected bruise susceptibility in apples and pears (García *et al.*, 1995), whereas an increased bruise level in ‘Red’ and ‘Golden Delicious’ apples caused changes of weight loss from 1.9% to 4.1% (Zhang, 1994). A greater water loss in ‘Oso Grande’ strawberries (11%) related to the lower anthocyanin level and other soluble phenolic contents after storage at 1°C for 8 days (Nunes *et al.*, 2005a).

The colour changes in bruised strawberries were associated a reduction of colour attributes (L*, a* and h* values), which may relate to anthocyanin leakage from bruise damage due to an increase of EC value and a reduction of firmness. Nevertheless, the impact damage in strawberries had no effect on weight loss during cool temperature storage for 3 days. An increase in weight loss could affect higher firmness and bruise damage due to less cell turgidity.

4.7 CONCLUSION

The different seasons of cultivation affected the preharvest quality and damage of ‘Elsanta’ and ‘Sonata’ strawberries. The winter cultivation provided more uniform fruit size, firmer fruit, lower bruise damage and lower EC value for both ‘Elsanta''and ‘Sonata’ strawberries than for the summer cultivation. After a drop test (5 times) onto mild steel and cool storage, the percentage of impact damage of both cultivars from the summer cultivation was higher than from the winter cultivation. The impact bruise of ‘Elsanta’ and ‘Sonata’ cultivars gave a similar impact bruise (%) and severity score ranges after impact test and cool storage.

An increase of the drop height level from 0 to 1000 mm was mainly associated with an increase of impact damage after impact test on day 0 and day 3. Immediately after the impact test (day 0), the drop height of 750 mm showed the maximum height limit for a severity score over 3 levels (acceptable score). After cool storage at 10^{o}C and 70% RH for 3 days, there was an increase of development of dry bruise and wet bruise. A punnet dropped from a height of 500 mm was considered to be the maximum height for an acceptable score of strawberry bruising after cool storage.

Immediately after the impact test and cool storage, the EC method showed a stronger correlation with wet bruise and severity score than the puncture, compression and respiration rate measurements, respectively. The EC value on the initial day could predict wet bruise, with different severities of wet bruise after cool storage at 10^{o}C for 3 days. In this impact experiment, the EC method (non-destructive method) is suggested for use as an indicator and predictor for bruised strawberry fruits through to cool storage for 3 days. Future research should therefore concentrate on the application of the EC method as a rapid method for bruise determination in a whole strawberry punnet. Also, mathematical modelling with a simple linear regression is suggested to assist in the study of the application of the EC method to predict the wet bruise of strawberries.

CHAPTER 5
VIBRATION TESTS ON THE QUALITY AND DAMAGE TO 'ELSANTA' AND 'SONATA' STRAWBERRIES IN THE WINTER AND SUMMER CULTIVATIONS

5.1 INTRODUCTION

Simulation tests attempt to evaluate a packaging system that imitates the actual transport situation (Sek, 1996). The study of simulated truck transport in the laboratory was recommended for separately analysing shock and vibration by removing the shock value (Lu *et al.*, 2008). There have been a number of simulated vibration studies involving factors affecting quality and damage of fresh produce. The three most important factors affect simulated vibration, namely frequency (Hz), acceleration (*g*) and exposure time (sec). For instance, Tabatabaekoloor *et al.* (2013) reported that the acceleration of 0.7 *g* at a frequency of 13 Hz gave the highest damage to kiwifruits when compared with a lower acceleration (0.3 *g*) at a lower frequency (7.5 Hz). Sharan *et al.* (2009) found that threefold increase in exposure time also caused the percentage of tomato damage to double.

A considerable quantity of literature has been published on the simulated vibration of strawberries. The previous studies of simulated conditions on strawberry bruise showed acceleration of 0.6-1.6 *g* at a frequency of 5-10 Hz for an exposure time of 40-3600 sec (Fischer *et al.*, 1992; Jiang *et al.*, 2001; Nakamura *et al.*, 2007b; Nakamura *et al.*, 2008). In the case of actual transport, all frequencies (3.35, 7 and 13.5 Hz) with acceleration of 0.02-0.185 *g* caused strawberry damage during transport, whereas the peak of vertical acceleration was at 3.35 Hz (Kojima *et al.*, 1999). The quality changes of strawberries caused by bruise after a vibration test include for example; an increased respiration rate and a reduction of firmness (Tatara *et al.*, 1999; Nakamura *et al.*, 2008). What is not clear is the effect of vibration test on the respiration rate pattern of strawberries (Fischer *et al.*, 1992). In a previous piece of research, there was a strong correlation between the conductivity and the percentage of pared fruits and the damage index of strawberries (Jiang *et al.*, 2001). Furthermore, until recently, there has been little published research of correlation between bruise damage and EC value, firmness and respiration rate of fresh fruits, particularly in strawberries.

Therefore, the hypotheses of this vibration test are:

a) there will be a higher level of damage on summer grown crops of ‘Elsanta’ and ‘Sonata’ cultivars than winter grown.
b) There will be no difference in vibration bruise between ‘Elsanta’ and ‘Sonata’ cultivars.
c) An increase in frequency and exposure time will give more vibration bruise for both cultivars after cool storage.
d) Greater exposure time after storage will give greater vibration bruise for all frequencies.
e) Developing a bruise indicator and a predictor from the vibration test, the EC technique will give a stronger relationship with strawberry bruise than firmness tests and respiration rate measurement.

Therefore, the objectives of the studies reported and discussed in this chapter were to determine the effects of the frequency and exposure time of vibration test on the quality and bruise of packed ‘Elsanta’ and ‘Sonata’ strawberries from the winter and summer cultivations. The correlation coefficient (*r*) between the objective methods of bruise determinations (EC method, firmness tests and respiration rate measurement) was analysed with subjective methods using bruise incidence and visual score from the vibration test. The developing non-destructive method of a greater correlation value was used as a bruise indicator and a bruise predictor from the vibration bruise of strawberries.

5.2 MATERIALS AND METHODS

5.2.1 Fruit materials

The harvesting periods of 'Elsanta' and 'Sonata' cultivars were carried out during the winter season (2014 and 2015) and summer season in 2014 (Figures 3.1 and 3.2). The strawberry fruits from the winter cultivation in 2015 were used in the respiration rate measurement. Strawberries were picked at full maturity (red colour) from the greenhouse at Writtle College with the same maturity index as the fruits for the impact test. The fruit sample preparation has been described in Chapter 3 (general materials and methods) (section 3.2). Briefly, the packed fruits in PET punnets were moved to the cool room for 4 hours until the pulp temperature dropped to the temperature range of $7.0 \pm 1^{o}C$. Following which, the packed strawberries weighing 250 g were sealed on the top of the punnet 2 hours prior to the vibration test.

5.2.2 Effect of the frequency and exposure time of vibration test on the quality of packed strawberries in punnet

Strawberry punnets were randomly allocated to treatments prior to the vibration test. The punnets were packed in corrugated common footprints (CCFs). In the case of no full packing (10 punnets), a plastic bag of 250 ml water was packed in punnet instead of strawberry fruits. The vibration levels were controlled using an orbital shaker at a fixed amplitude of 16 mm (Stuart SSL1, UK) (Figure 5.1).

The experimental plan of vibration test was undertaken using completely randomized design (CRD) for three treatments, including control (no vibration test). The four treatments were control and three frequency levels at 3, 4 and 5 Hz for each of the three exposure times for 50, 100 and 150 sec. Five (winter cultivation) and three (summer cultivation) punnets (replicates) were used in the vibration test. The acceleration (*g*) level of the orbital shaker was also measured by spectral vibration logger SVR101 (MadgeTech, USA). In this study, therefore, the frequencies and total acceleration levels (T-axis) of the vibration test were 3 Hz (0.4 *g*), 4 Hz (0.8 *g*), and 5

Hz (1.1 *g*). The acceleration level in this study also was determined on the basis of the previous studies presented by Fischer *et al.* (1992) and Jiang *et al.* (2001).

5.3 QUALITY DETERMINATION

The determinations of quality and damage were physicochemical properties and visual score as described in Chapter 3 (general materials and methods) (section 3.5). The quality determination also was carried out on day 0 and after storage (10±1^{o}C and 70±5% RH) for 3 days. The respiration rate measurement of strawberries was explained in Chapter 3 (section 3.5.5). CO_2 production (%) was measured throughout storage at 10^{o}C for 4 days and then reported in mgCO_2/kg.hr.

Figure 5.1: Orbital shaker (Stuart SSL1) for vibration test of strawberry punnets. *Source*: Chaiwong (2015).

5.4 DATA ANALYSIS

The collected data was analysed using SPSS version 16.0. Analysis of variance was performed in each strawberry cultivar and cultivation, and the means were separated using Duncan's multiple range test (DMRT) at $p \leq 0.05$. The correlation coefficient (*r*) between the objective methods (EC, firmness and respiration rate) and bruise damage from vibration test was performed using Pearson's correlation at $p \leq 0.01$.

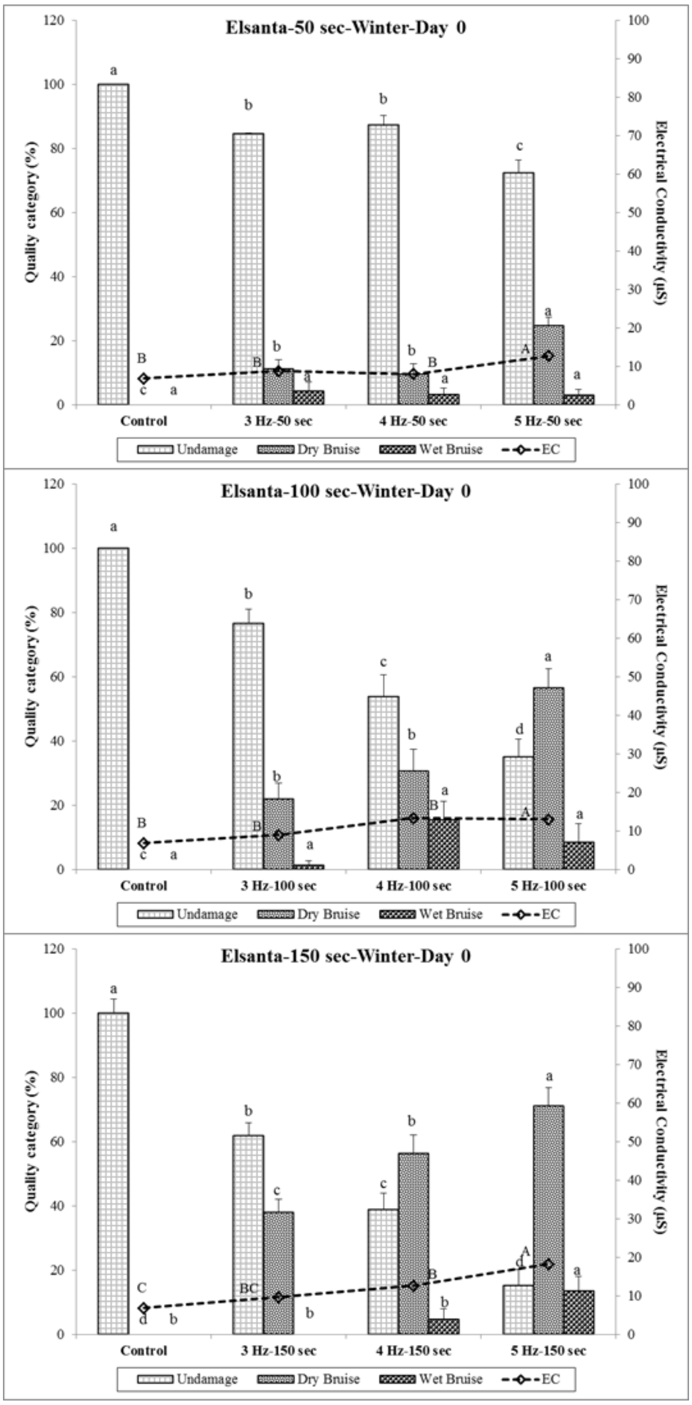
5.5 RESULTS

The simulated vibration conditions of 'Elsanta' and 'Sonata' cultivars were varied at three frequency levels (3, 4 and 5 Hz) with three periods of exposure time (50, 100 and 150 sec). Hence, the total acceleration levels (T-axis) at each frequency were also 0.4 *g* (3 Hz), 0.8 *g* (4 Hz), and 1.1 *g* (5 Hz). In this vibration study, the average values of the results are compared among the four treatments (control, 3, 4 and 5 Hz) for each exposure time.

5.5.1 The effect of vibration test on the quality, bruise and respiration rate of 'Elsanta' strawberries

5.5.1.1 Percentage of quality category and electrical conductivity of 'Elsanta' strawberries

Immediately before the vibration test (day 0), 'Elsanta' strawberries in the winter production had no bruise damage (100% undamaged fruits) before the vibration test (Figure 5.2). The percentage of wet bruise (summer production) from all vibration conditions (>40%) was higher than those of the winter production (<20%) (Figures 5.2 and 5.4). The increases of frequency level and exposure time affected notably a reduction of undamaged fruits, and the rise in the number of wet bruise and electrical conductivity values (Figures 5.2 and 5.4). In the winter cultivation, the frequency of 5 Hz for 150 sec caused the lowest level of undamaged fruits (approximate 15%) as compared to nearly 72% and 34% for the frequency of 3 and 4 Hz at 150 sec, respectively (Figure 5.2). These results confirm that the vibration at 5 Hz for 150 sec in the summer cultivation also had the lowest level of undamaged fruits (Figure 5.4). The initial electrical conductivity (EC) value in the winter cultivation was 6.81 µS, and then after vibration test at 5 Hz (50 to 150 sec), the highest EC level was a range value of 12 to 18 µS ($p \leq 0.05$) (Figure 5.2). Nevertheless, the EC value of control samples (no vibration test) in the summer cultivation started from 21.86 µS, which was a higher level than those fruits in the winter season. After vibration test, the EC value of summer strawberries reached to approximately 40 to 60 µS at the frequency of 4 and 5 Hz for 150 sec (Figure 5.4). Over the entire of storage at 10^{o}C for 3 days, there was a sharp increase in the percentage of dry bruise. There was not a significant difference in the EC value at 3 and 4 Hz, but there was at 5 Hz (150 sec) ($p \leq 0.05$) (Figures 5.3 and 5.5).



(A)

(B)

(C)

Figure 5.2: Effect of vibration test for 50 sec (A), 100 sec (B) and 150 sec (C) on quality category and electrical conductivity of 'Elsanta' strawberries from the winter cultivation at day 0. Different letters in the different frequency levels for DMRT test indicate significant differences at p≤0.05. Values are the mean ±S.E. from 5 replicates.

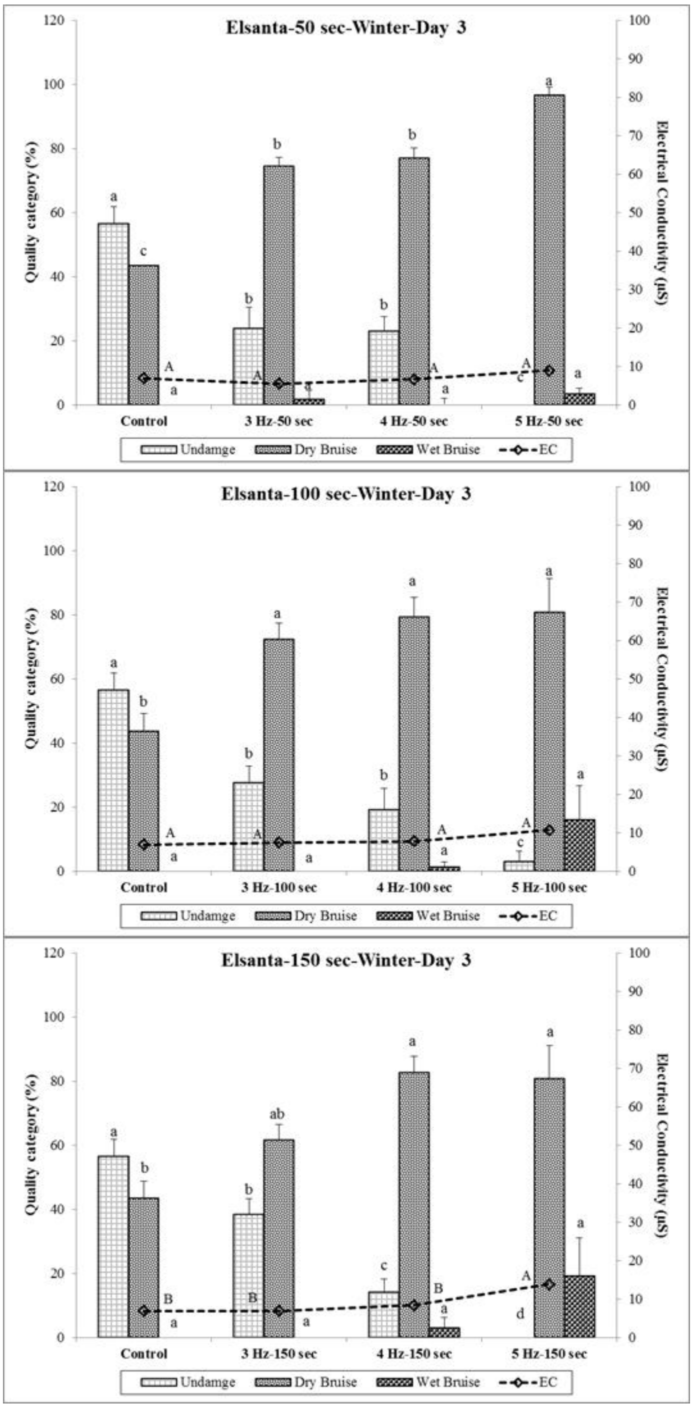
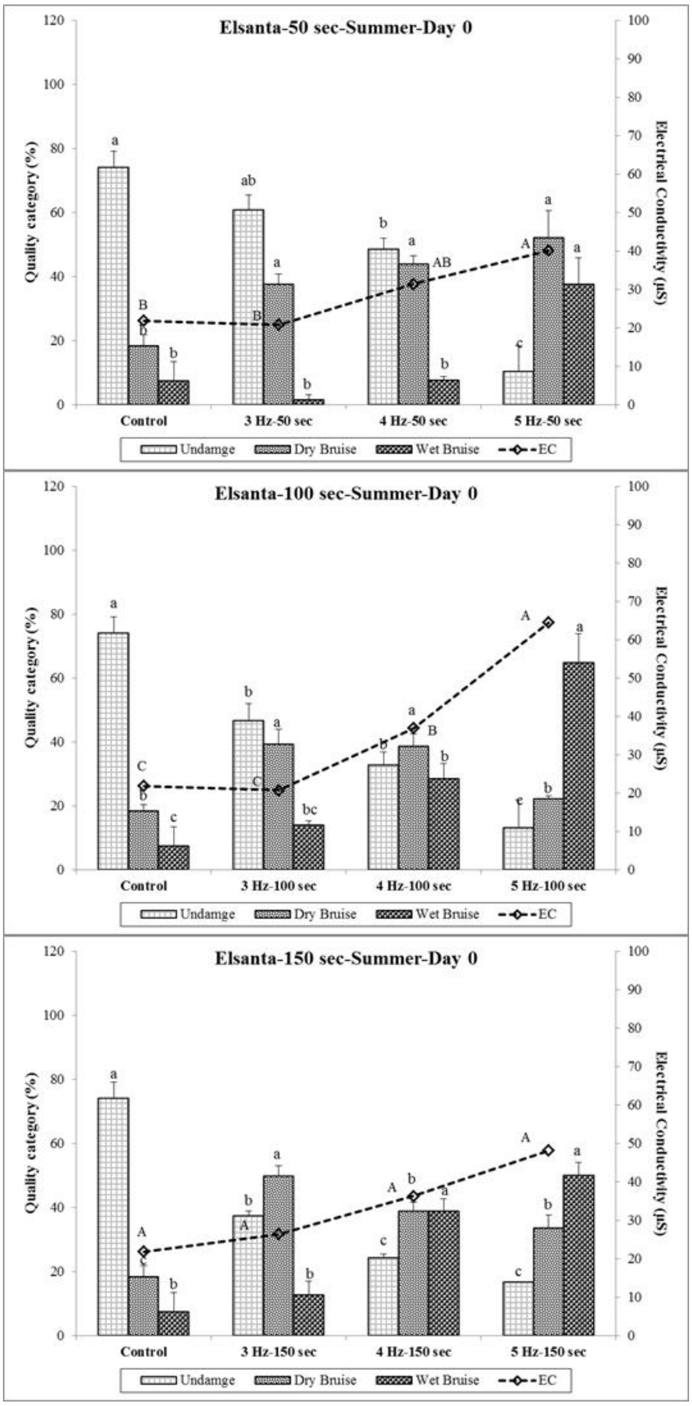


Figure 5.3: Effect of vibration test for 50 sec (A), 100 sec (B) and 150 sec (C) on quality category and electrical conductivity of 'Elsanta' strawberries from the winter cultivation at day 3. Different letters in the different frequency levels for DMRT test indicate significant differences at $p \leq 0.05$. Values are the mean ±S.E. from 5 replicates.

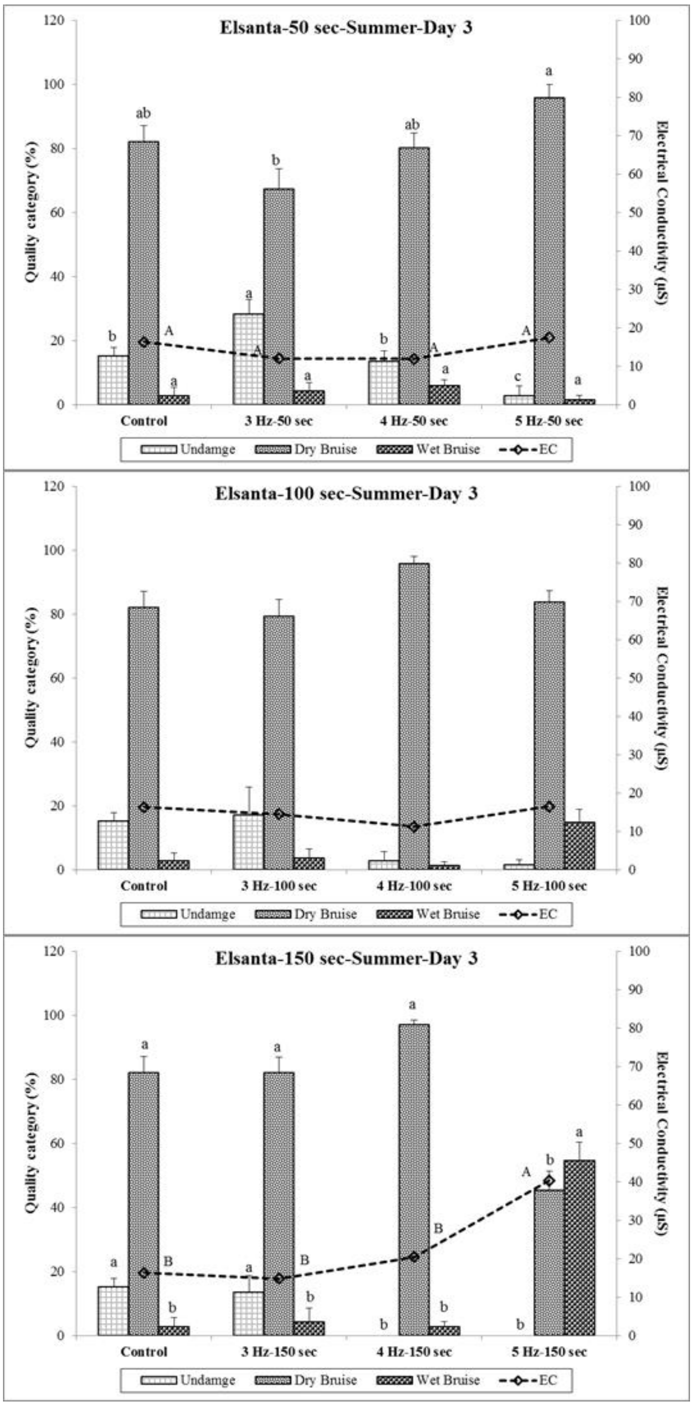


(A)

(B)

(C)

Figure 5.4: Effect of vibration test for 50 sec (A), 100 sec (B) and 150 sec (C) on quality category and electrical conductivity of 'Elsanta' strawberries from the summer cultivation at day 0. Different letters in the different frequency levels for DMRT test indicate significant differences at $p \leq 0.05$. Values are the mean ±S.E. from 3 replicates.



(A)

(B)

(C)

Figure 5.5: Effect of vibration test for 50 sec (A), 100 sec (B) and 150 sec (C) on quality category and electrical conductivity of 'Elsanta' strawberries from the summer cultivation at day 3. Different letters in the different frequency levels for DMRT test indicate significant differences at $p \leq 0.05$. Values are the mean ±S.E. from 3 replicates

5.5.1.2 Fruit weight, firmness (puncture and compression) and severity score of 'Elsanta' strawberries

The fruit size of 'Elsanta' strawberries in the winter production (18-20 g per fruit) was bigger than in the summer production (11-14 g per fruit) by around 10 g in each fruit. Overall, the fruit size of 'Elsanta' cultivar had no statistically significant difference among the four treatments in each exposure time and storage duration ($p>0.05$) (Tables 5.1 and 5.2).

Immediately after the vibration test for 50, 100 and 150 sec (day 0), a significant difference was not observed in the fruit firmness (puncture) for both seasons between the control fruits (no vibration test) and the vibrated fruits ($p>0.05$) (Table 5.1). After the entire storage for 3 days, control fruits had the highest firmness of strawberries from the winter production ($p\leq0.05$). In the summer production, no vibration treatment (control) also remained with the greatest firmness, particularly at the exposure time for 150 sec ($p\leq0.05$) (Table 5.2). For the vibration method, the compression test was able to detect a different firmness value more than the puncture test (Tables 5.1 and 5.2), which was different from the result of the impact test (Tables 4.1 and 4.3).

A reduction of severity score related to the increases of frequency level and the vibrating period of testing. The overall severity score of vibrated fruits was approximately at score 3 (acceptable score) after the end of storage. However, the severity score of the summer strawberries was not significantly different in all treatments (50, 100 and 150 sec) ($p>0.05$) (Table 5.2).

Table 5.1: Effect of vibration test on fruit weight, firmness and severity score of 'Elsanta' strawberries from the winter and summer cultivations at day 0.

Treatment	Weight (g)	Puncture (kg)	Compression (kg)	Severity score
		Elsanta-Day 0-Winter		
Control	21.43±0.20	0.504±0.012	1.488±0.091	4.9[a]±0.04
3 Hz - 50 sec	18.99±1.30	0.524±0.022	1.520±0.050	4.8[b]±0.03
4 Hz - 50 sec	18.99±1.30	0.512±0.027	1.465±0.031	4.8[b]±0.04
5 Hz - 50 sec	18.41±1.26	0.511±0.016	1.470±0.017	4.7[b]±0.04
Control	21.43[a]±0.20	0.504±0.012	1.488±0.091	4.9[a]±0.04
3 Hz - 100 sec	18.20[b]±0.27	0.478±0.013	1.417±0.011	4.7[b]±0.05
4 Hz - 100 sec	17.42[b]±0.23	0.467±0.021	1.382±0.028	4.5[c]±0.09
5 Hz - 100 sec	17.84[b]±0.39	0.472±0.012	1.406±0.045	4.4[c]±0.04
Control	21.43[a]±0.20	0.504±0.012	1.488±0.091	4.9[a]±0.04
3 Hz - 150 sec	20.50[ab]±0.38	0.504±0.015	1.510±0.077	4.8[ab]±0.04
4 Hz - 150 sec	19.60[b]±0.42	0.497±0.023	1.445±0.035	4.7[b]±0.06
5 Hz - 150 sec	20.63[a]±0.19	0.510±0.027	1.488±0.046	4.2[c]±0.13
		Elsanta-Day 0-Summer		
Control	14.50[a]±1.14	0.360±0.022	1.266±0.067	4.8[a]±0.05
3 Hz - 50 sec	11.14[b]±0.48	0.350±0.016	1.100±0.000	4.7[a]±0.03
4 Hz - 50 sec	11.35[b]±0.22	0.340±0.105	1.130±0.023	4.6[a]±0.03
5 Hz - 50 sec	11.57[b]±0.57	0.310±0.016	1.074±0.058	4.0[b]±0.09
Control	14.50[a]±1.14	0.362±0.022	1.266[a]±0.067	4.8[a]±0.05
3 Hz - 100 sec	10.98[b]±0.53	0.312±0.010	1.133[ab]±0.067	4.5[a]±0.09
4 Hz - 100 sec	10.60[b]±0.53	0.317±0.040	0.916[b]±0.082	4.3[a]±0.06
5 Hz - 100 sec	10.46[b]±0.24	0.310±0.007	0.980[b]±0.098	3.4[b]±0.42
Control	14.50[a]±1.14	0.362±0.022	1.266[a]±0.007	4.8[a]±0.05
3 Hz - 150 sec	10.18[b]±0.31	0.352±0.017	1.019[b]±0.011	4.5[ab]±0.09
4 Hz - 150 sec	10.72[b]±0.25	0.331±0.016	1.166[ab]±0.059	3.9[bc]±0.32
5 Hz - 150 sec	10.65[b]±0.05	0.294±0.000	0.803[c]±0.031	3.7[c]±0.06

Means with different letters in the same column at each day and exposure time are significantly different at p≤0.05. Values are the mean ±S.E. from 5 replicates (winter) and 3 replicates (summer).

Table 5.2: Effect of vibration test on fruit weight, firmness and severity score of 'Elsanta' strawberries from the winter and summer cultivations at day 3.

Treatment	Weight (g)	Puncture (kg)	Compression (kg)	Severity score
		Elsanta-Day 3-Winter		
Control	19.51±0.45	0.627±0.018	1.952^{a}±0.051	4.5^{a}±0.08
3 Hz - 50 sec	18.41±1.65	0.552±0.033	1.609^{b}±0.070	4.0^{b}±0.07
4 Hz - 50 sec	19.36±1.00	0.538±0.040	1.541^{b}±0.083	4.0^{b}±0.05
5 Hz - 50 sec	18.91±0.93	0.551±0.027	1.540^{b}±0.040	2.9^{c}±0.24
Control	19.51±0.45	0.627^{a}±0.018	1.952^{a}±0.051	4.5^{a}±0.08
3 Hz - 100 sec	19.91±0.66	0.521^{b}±0.007	1.509^{b}±0.036	4.3^{a}±0.12
4 Hz - 100 sec	19.88±0.78	0.521^{b}±0.007	1.509^{b}±0.036	4.0^{a}±0.18
5 Hz - 100 sec	19.49±0.82	0.488^{b}±0.029	1.433^{b}±0.043	3.3^{b}±0.26
Control	19.51±0.45	0.627^{a}±0.018	1.952^{a}±0.051	4.5^{a}±0.08
3 Hz - 150 sec	18.53±0.25	0.507^{b}±0.008	1.557^{b}±0.037	4.3^{ab}±0.07
4 Hz - 150 sec	19.03±0.15	0.519^{b}±0.019	1.391^{c}±0.052	3.9^{b}±0.15
5 Hz - 150 sec	18.54±0.77	0.454^{b}±0.033	1.496^{bc}±0.042	3.2^{c}±0.17
		Elsanta-Day 3-Summer		
Control	12.75±0.88	0.436±0.012	1.444±0.057	4.2±0.09
3 Hz - 50 sec	10.95±0.18	0.354±0.033	1.185±0.103	4.4±0.00
4 Hz - 50 sec	10.39±0.38	0.357±0.013	1.179±0.078	4.2±0.09
5 Hz - 50 sec	11.39±0.76	0.413±0.030	1.210±0.106	4.0±0.17
Control	12.75±0.88	0.436±0.012	1.441±0.057	4.2±0.09
3 Hz - 100 sec	11.41±0.49	0.375±0.032	1.255±0.132	4.1±0.14
4 Hz - 100 sec	10.80±0.54	0.389±0.052	1.327±0.089	3.9±0.26
5 Hz - 100 sec	11.48±0.23	0.367±0.046	1.217±0.035	3.6±0.15
Control	12.75±0.88	0.436^{a}±0.012	1.441^{a}±0.057	4.2±0.09
3 Hz - 150 sec	10.81±0.43	0.403^{ab}±0.010	1.312^{a}±0.057	4.1±0.14
4 Hz - 150 sec	10.66±0.34	0.333^{bc}±0.044	1.234^{ab}±0.055	3.9±0.26
5 Hz - 150 sec	10.86±0.61	0.299^{c}±0.008	1.061^{c}±0.093	3.6±0.15

Means with different letters in the same column at each day and exposure time are significantly different at $p \leq 0.05$. Values are the mean ±S.E. from 5 replicates (winter) and 3 replicates (summer).

5.5.1.3 TSS (%), TA (%) and TSS:TA ratio of 'Elsanta' strawberries

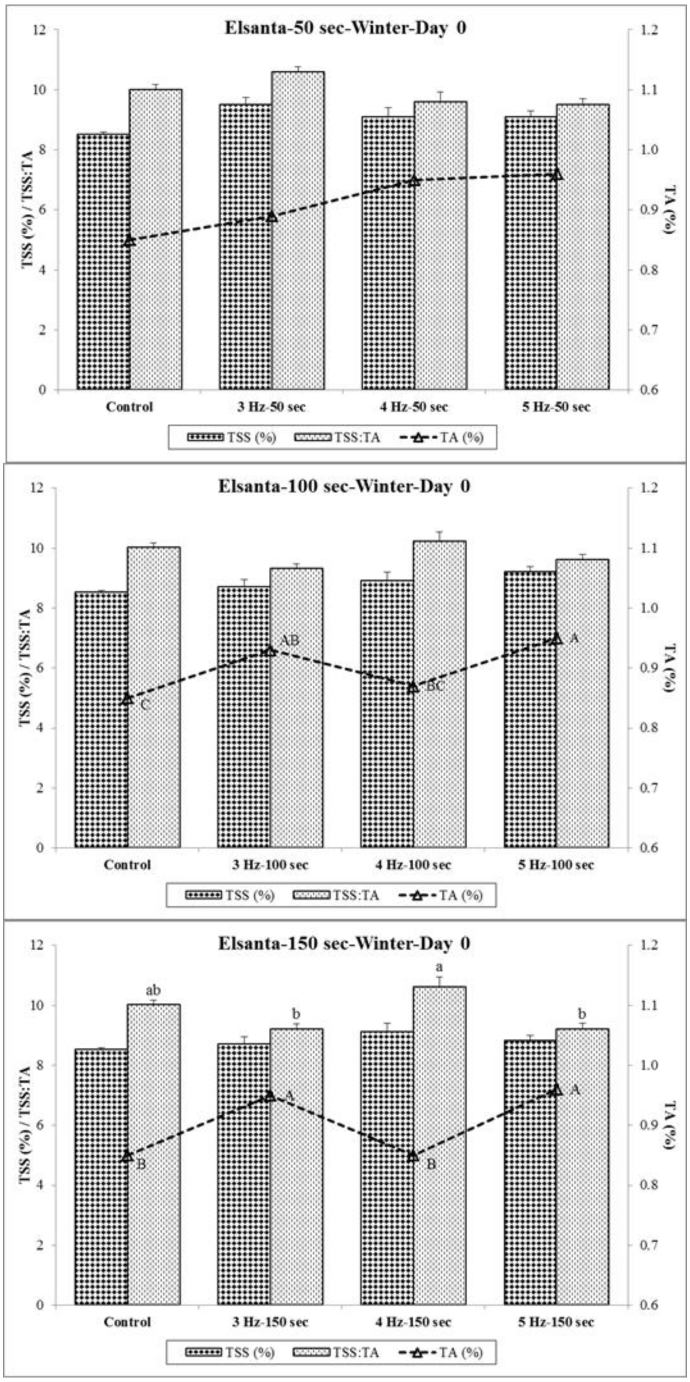
The TSS contents of 'Elsanta' strawberries from the winter and summer cultivations were over 8% TSS (Figures 5.6-5.9). After harvesting, the approximate TA content of fruits from the summer production (1.0%) was at a higher level than that from the winter season (0.9%) (Figures 5.6 and 5.8). The vibration treatments did not notably affect overall contents of TSS, TA and TSS:TA after harvesting and at low temperature storage (Figures 5.6-5.9).

5.5.1.4 Fruit surface colour (L*, a*, b*, h*, and C* values) of 'Elsanta' strawberries

The vibrated punnets were not observed to have a significant change in the overall value of fruit surface colour in 'Elsanta' strawberries after harvesting and over the entire test period ($p \leq 0.05$) (Figures 5.10-5.12). The hue (h*) values of the vibrated fruits for 100 and 150 sec were lower than control treatment (Figures 5.11 and 5.12).

5.5.1.5 Weight loss (%) of 'Elsanta' strawberries

As shown in Table 5.3, the weight loss of 'Elsanta' strawberries increased through to the end of storage for 3 days. The average weight loss (%) of packed strawberries was nearly 2.5% in the winter cultivation and 1.5% in the summer cultivation. The overall weight loss (%) during low temperature storage was not significantly different ($p > 0.05$). However, the control punnets at 150 sec (winter) or at 50 sec (summer) had the greatest weight loss when compared with the vibrated fruits ($p \leq 0.05$).



(A)

(B)

(C)

Figure 5.6: Effect of vibration test for 50 sec (A), 100 sec (B) and 150 sec (C) on TSS (%), TA (%) and TSS:TA ratio contents of 'Elsanta' strawberries from the winter cultivation at day 0. Different letters in the different frequency levels for DMRT test indicate significant differences at p≤0.05. Values are the mean ±S.E. from 5 replicates.

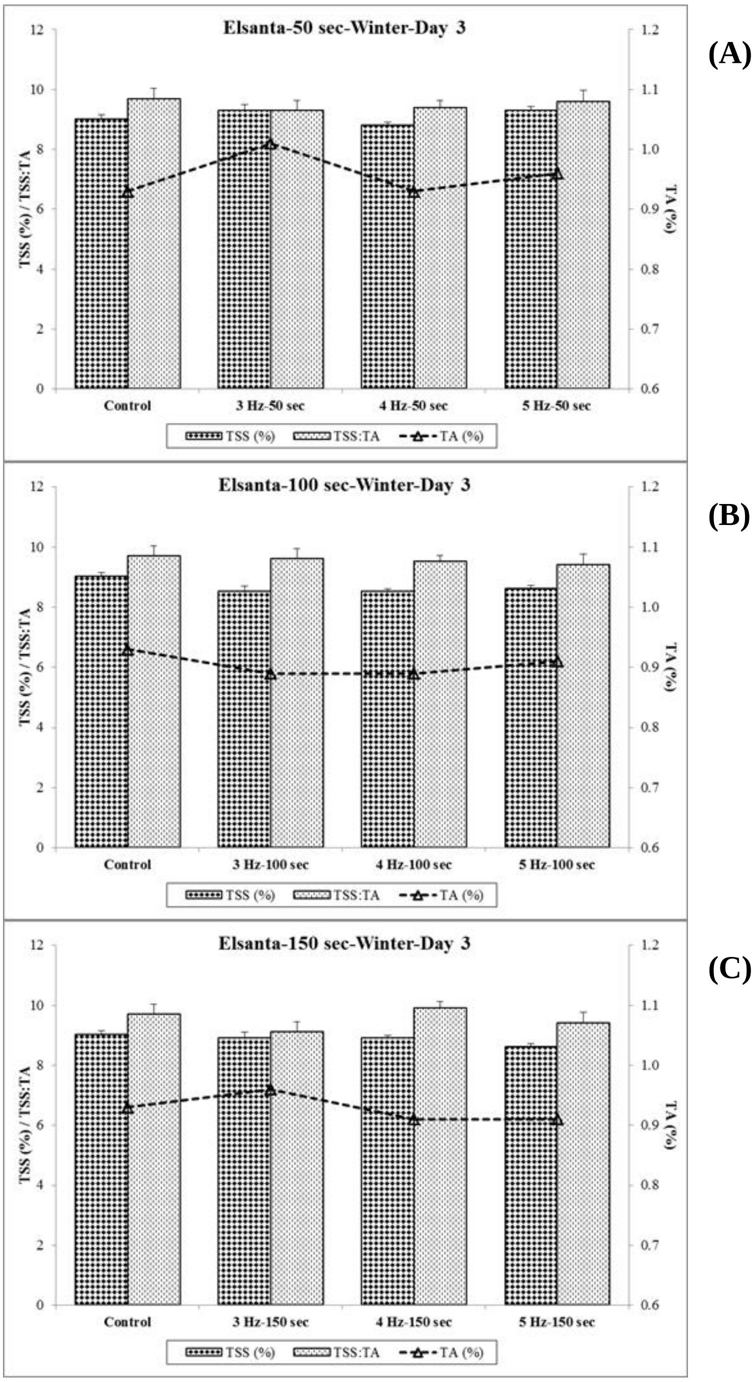
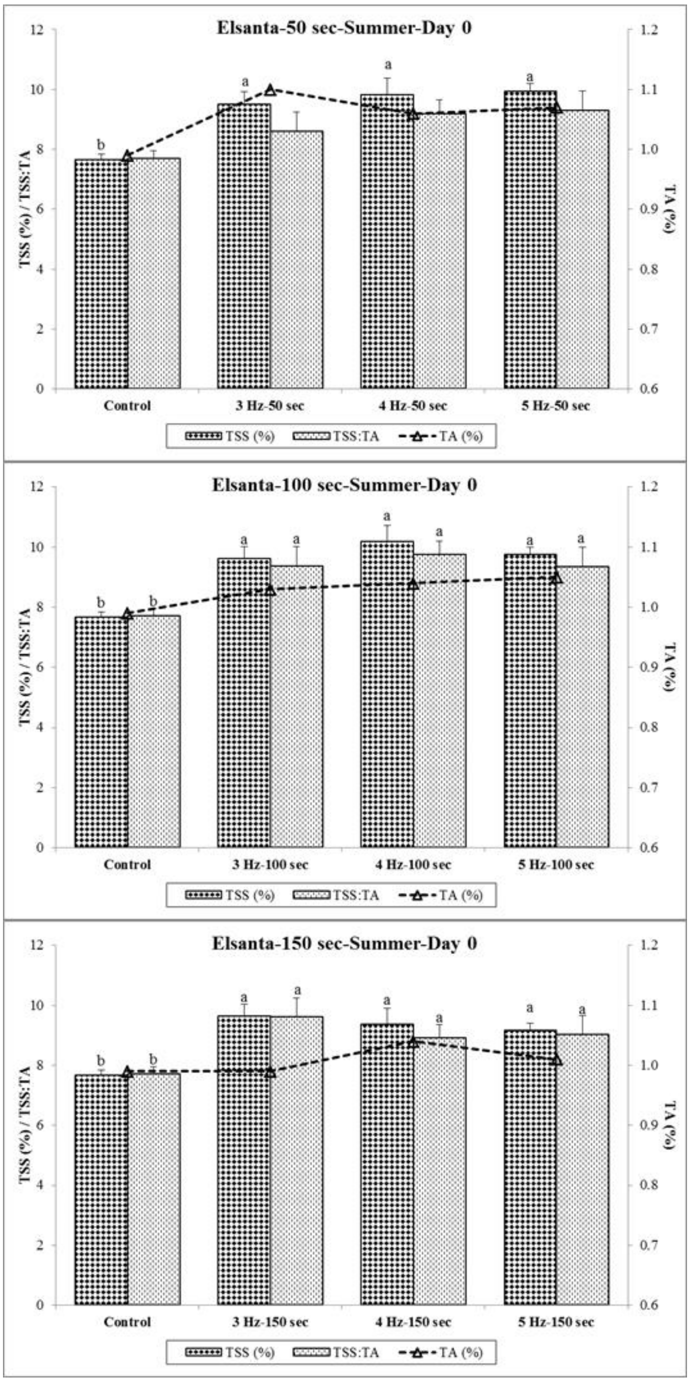


Figure 5.7: Effect of vibration test for 50 sec (A), 100 sec (B) and 150 sec (C) on TSS (%), TA (%) and TSS:TA ratio contents of 'Elsanta' strawberries from the winter cultivation at day 3. Different letters in the different frequency levels for DMRT test indicate significant differences at $p \leq 0.05$. Values are the mean ±S.E. from 5 replicates.



(A)

(B)

(C)

Figure 5.8: Effect of vibration test for 50 sec (A), 100 sec (B) and 150 sec (C) on TSS (%), TA (%) and TSS:TA ratio contents of 'Elsanta' strawberries from the summer cultivation at day 0. Different letters in the different frequency levels for DMRT test indicate significant differences at $p \leq 0.05$. Values are the mean ±S.E. from 3 replicates.

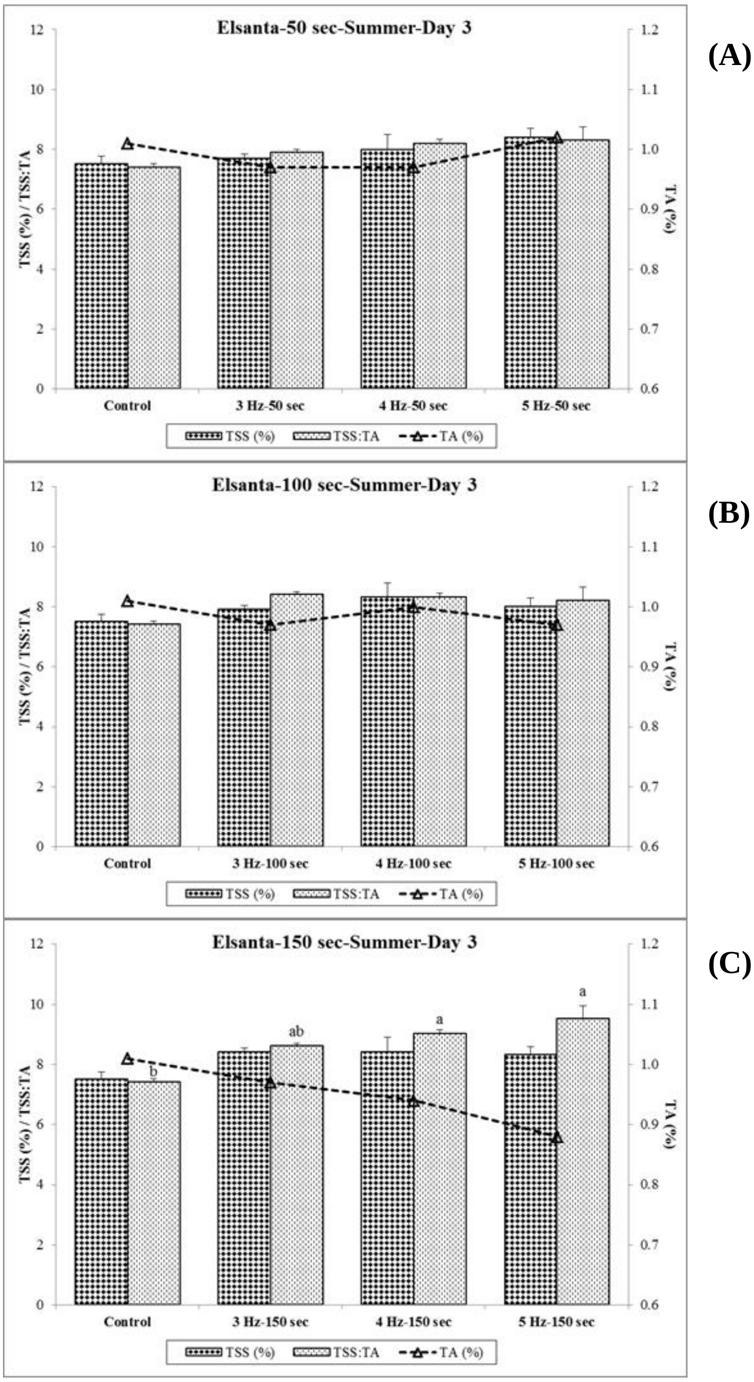


Figure 5.9: Effect of vibration test for 50 sec (A), 100 sec (B) and 150 sec (C) on TSS (%), TA (%) and TSS:TA ratio contents of 'Elsanta' strawberries from the summer cultivation at day 3. Different letters in the different frequency levels for DMRT test indicate significant differences at p≤0.05. Values are the mean ±S.E. from 3 replicates.

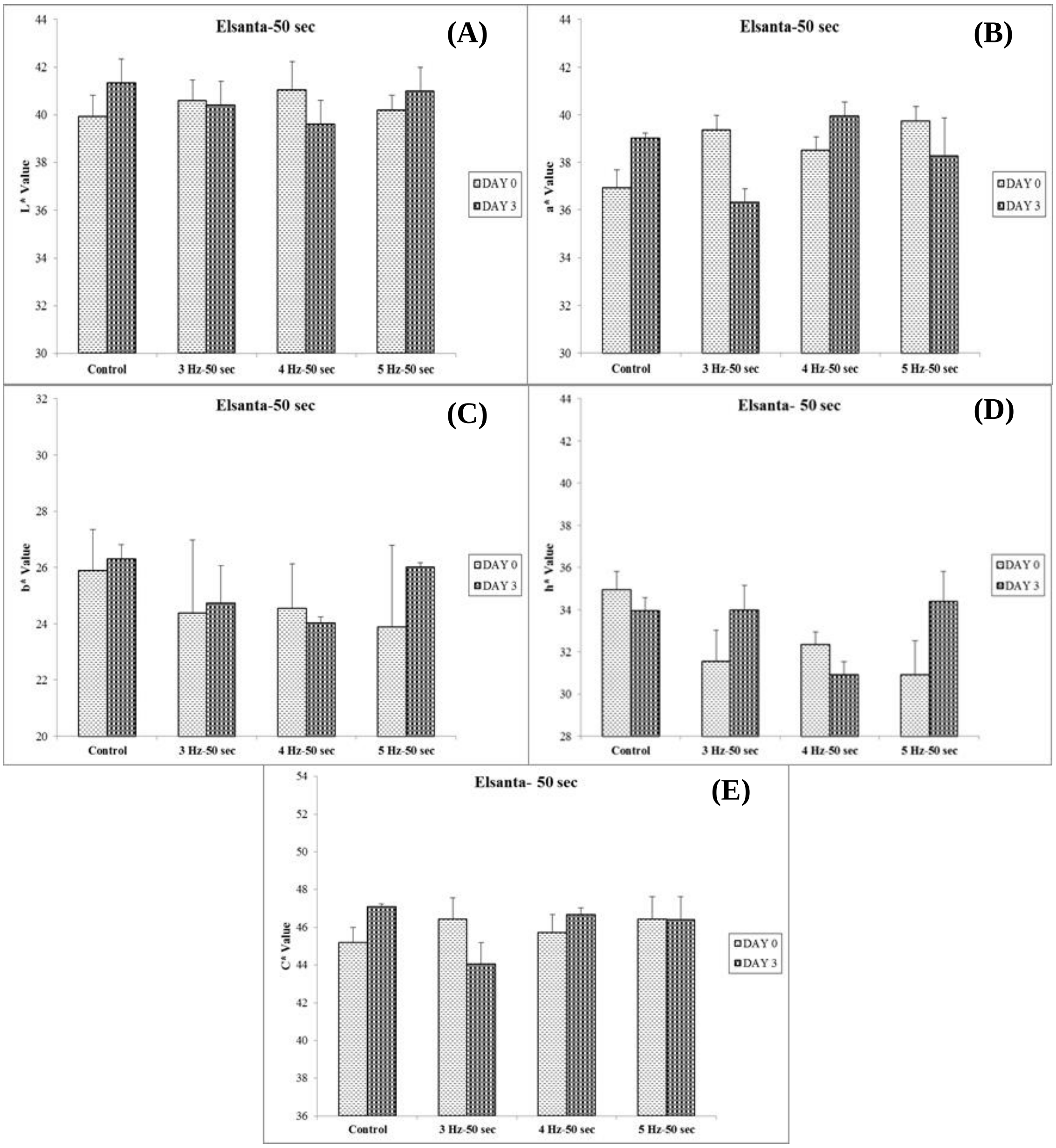


Figure 5.10: Effect of vibration test for 50 sec on the values of L* (A), a* (B), b* (C), h* (D) and C* (E) of 'Elsanta' strawberries from the summer cultivation at day 0 and day 3. Different letters in the different frequency levels for DMRT test indicate significant differences at $p \leq 0.05$. Values are the mean ±S.E. from 3 replicates.

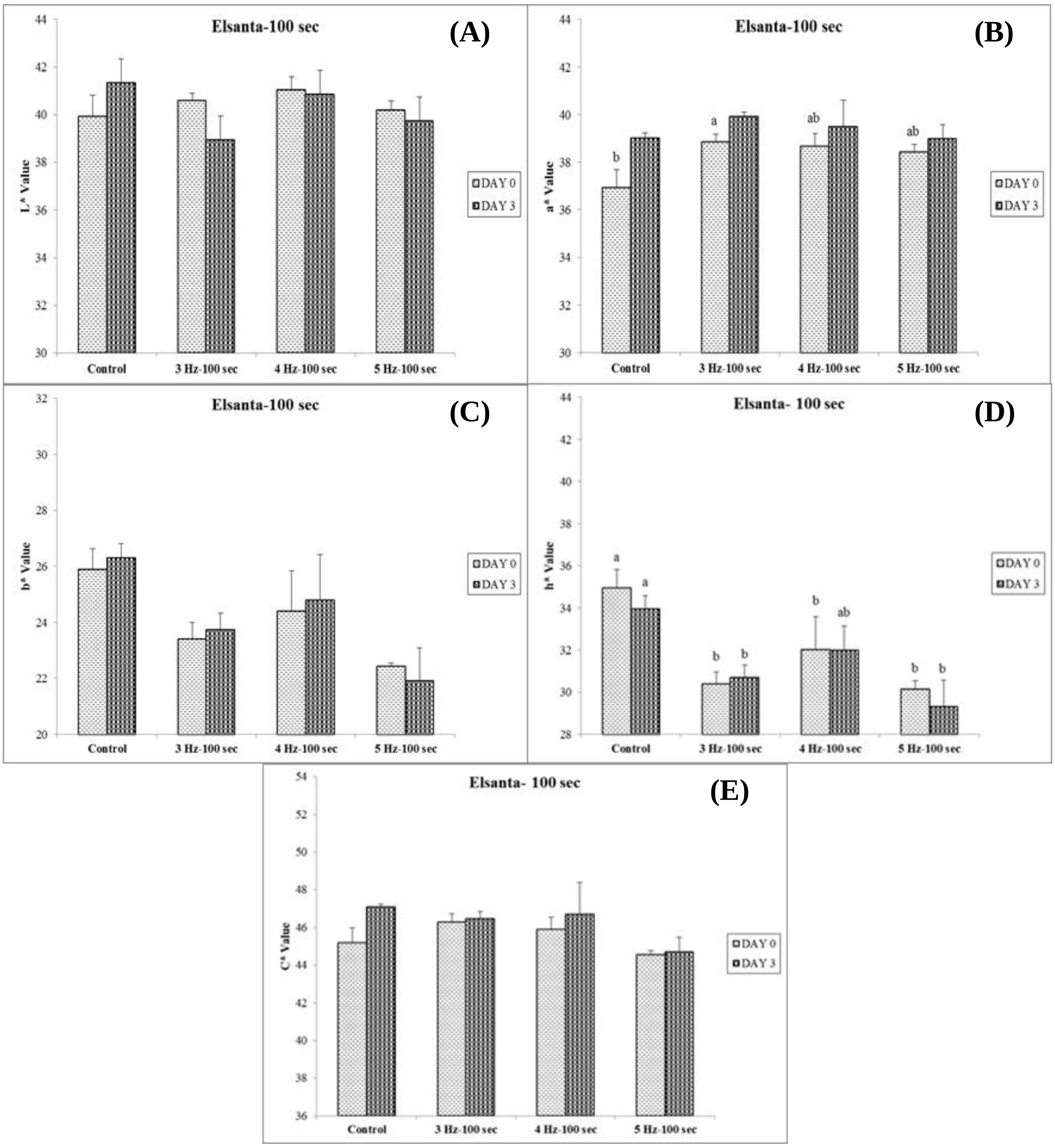


Figure 5.11: Effect of vibration test for 100 sec on the values of L* (A), a* (B), b* (C), h* (D) and C* (E) of 'Elsanta' strawberries from the summer cultivation at day 0 and day 3. Different letters in the different frequency levels for DMRT test indicate significant differences at p≤0.05. Values are the mean ±S.E. from 3 replicates.

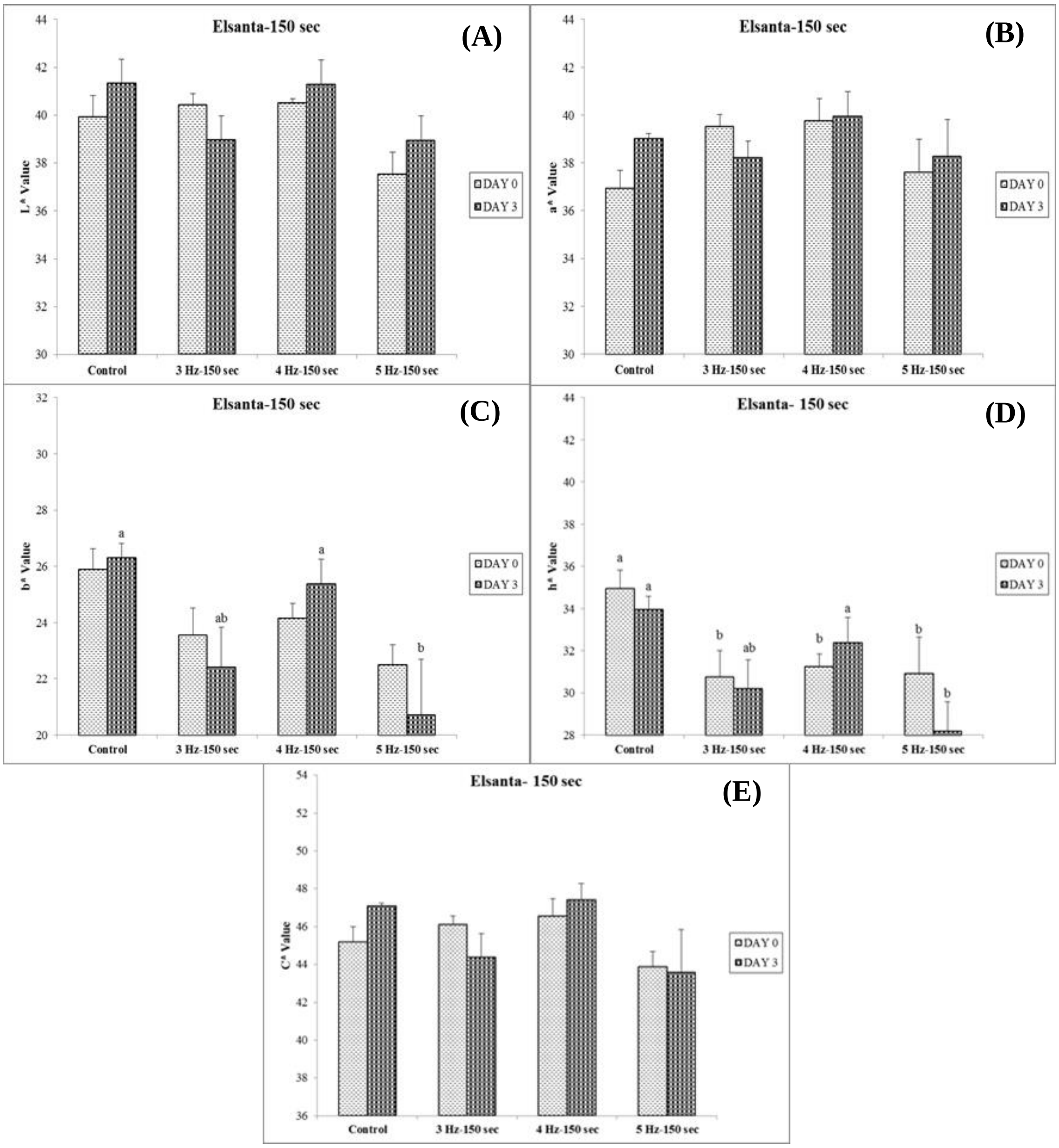


Figure 5.12: Effect of vibration test for 150 sec on the values of L* (A), a* (B), b* (C), h* (D) and C* (E) of 'Elsanta' strawberries from the summer cultivation at day 0 and day 3. Different letters in the different frequency levels for DMRT test indicate significant differences at $p \leq 0.05$. Values are the mean ±S.E. from 3 replicates.

Table 5.3: Effect of vibration test on weight loss (%) of 'Elsanta' strawberries from the winter and summer cultivations during storage at 10^{o}C for 3 days.

	Weight loss (%)		
Treatment	**Day 1**	**Day 2**	**Day 3**
	Elsanta-Winter		
Control	1.53±0.13	2.37±0.14	3.09±0.27
3 Hz - 50 sec	0.95±0.11	1.75±0.10	2.13±0.13
4 Hz - 50 sec	0.13±0.25	2.16±0.29	2.61±0.21
5 Hz - 50 sec	0.84±0.08	1.72±0.08	2.23±0.23
Control	1.53^{a}±0.13	2.37±0.14	3.09±0.27
3 Hz - 100 sec	1.04^{b}±0.05	1.81±0.09	2.23±0.13
4 Hz - 100 sec	0.99^{b}±0.05	1.93±0.10	2.43±0.15
5 Hz - 100 sec	1.02^{b}±0.08	1.98±0.26	2.40±0.26
Control	1.53^{a}±0.13	2.37^{a}±0.14	3.09^{a}±0.27
3 Hz - 150 sec	0.80^{b}±0.04	1.44^{b}±0.06	1.76^{b}±0.08
4 Hz - 150 sec	0.90^{b}±0.08	1.51^{b}±0.11	1.82^{b}±0.10
5 Hz - 150 sec	0.62^{b}±0.06	1.19^{b}±0.03	1.45^{b}±0.07
	Elsanta-Summer		
Control	1.05±0.02	1.74^{a}±0.02	1.95^{a}±0.02
3 Hz - 50 sec	0.88±0.14	1.18^{b}±0.14	1.39^{b}±0.12
4 Hz - 50 sec	0.85±0.06	1.16^{b}±0.12	1.42^{b}±0.12
5 Hz - 50 sec	0.71±0.17	0.93^{b}±0.18	1.18^{b}±0.20
Control	1.05±0.02	1.74±0.02	1.95±0.02
3 Hz - 100 sec	0.98±0.16	1.29±0.16	1.53±0.16
4 Hz - 100 sec	0.71±0.03	1.24±0.10	1.53±0.16
5 Hz - 100 sec	1.05±0.18	1.39±0.23	1.69±0.23
Control	1.06±0.02	1.74±0.02	1.95±0.02
3 Hz - 150 sec	0.95±0.10	1.33±0.19	1.71±0.23
4 Hz - 150 sec	1.09±0.26	1.45±0.31	1.71±0.29
5 Hz - 150 sec	0.95±0.25	1.40±0.20	1.75±0.23

Means with different letters in the same column at each day and exposure time are significantly different at $p \leq 0.05$. Values are the mean ±S.E. from 5 replicates (winter) and 3 replicates (summer).

5.5.1.6 Respiration rate, percentage of quality category and severity score of 'Elsanta' strawberries after vibration test

The respiration rate of 'Elsanta' strawberries was also repeated in the winter production 2015. The strawberry maturity was evaluated before the vibration test in the same way as for the impact test. The overall respiration rate of 'Elsanta' strawberries in winter cultivation (2015) was lower than in the summer cultivation (2014). At the initial hour (0 hour), the respiration rate of the control (no vibration) was 36.94 mgCO_2/kg.hr (winter) and 55.44 mgCO_2/kg.hr (summer). After the vibration test, the range of respiration rate in the winter and summer cultivations was 39-46 mgCO_2/kg.hr and 54-66 mgCO_2/kg.hr, respectively (Figures 5.13 and 5.14).

An increase of respiration rate led to the higher frequency level and exposure time. In the winter cultivation, the respiration rate of vibrated fruits for 50 sec was similar to control samples (Figure 5.13A). The highest respiration rate (46 mgCO_2/kg.hr) was found in the punnets vibrated at 4 and 5 Hz for 150 sec (Figure 5.13B-C). In the summer cultivation, the frequency of 5 Hz in each exposure time was observed to have the highest respiration rate (66 mgCO_2/kg.hr) (Figure 5.14).

After the end of low temperature storage for 96 hours (4 days), in the winter cultivation, the percentage of undamaged fruits and bruise was not significantly different between control and the punnets vibrated for 50 and 100 sec ($p>0.05$). The frequency of 5 Hz for 150 sec had the lowest rate of undamaged fruits (<20%). However, the severity score for all treatments was a score over 4 (Figure 5.15). The mould incidence occurred only on the fruits from the summer cultivation (Figure 5.16). The dry bruise from the vibration levels for 50 and 100 sec had no a significant difference among four treatments (Figures 5.15A-B and 5.16A-B). The frequency of 5 Hz for 150 sec gave the highest percentage of wet bruise at nearly 60%. All treatments had a severity score of over 3, except the frequency of 5 Hz for 150 sec.

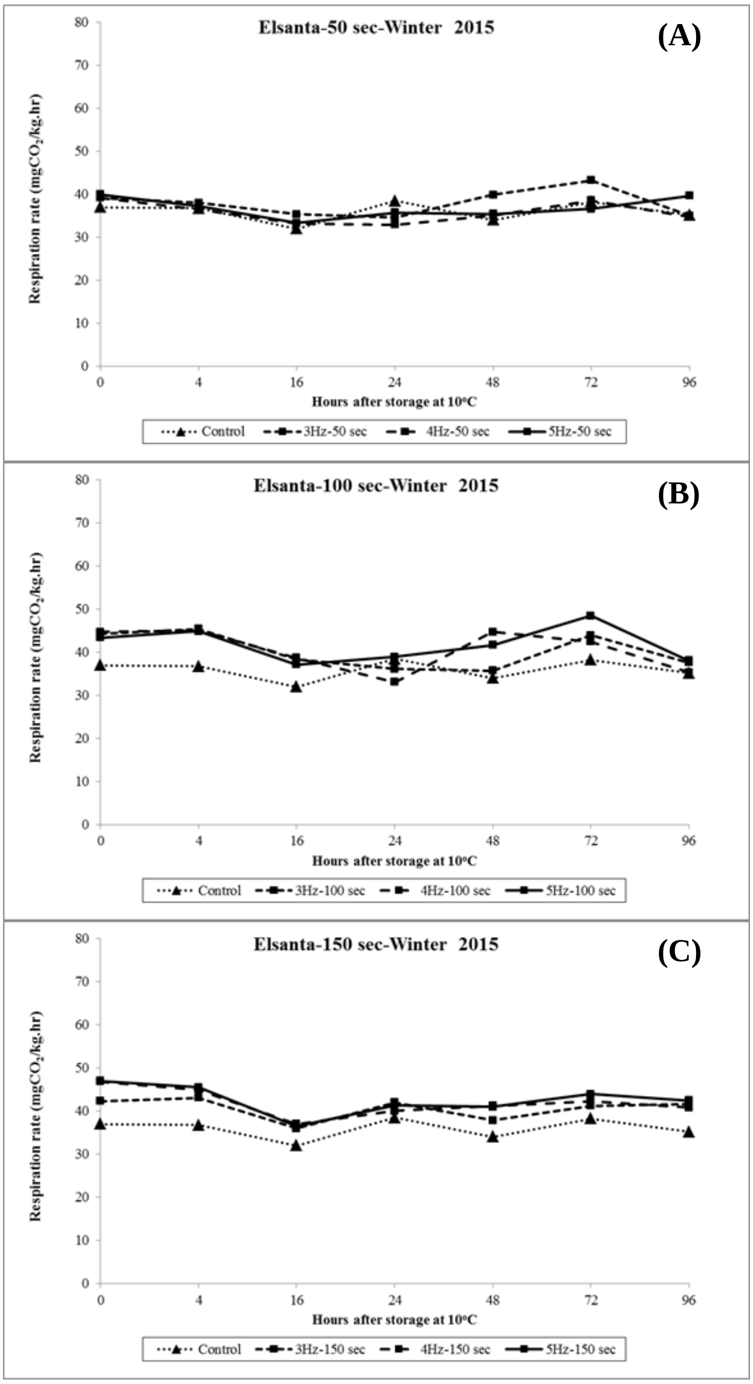


Figure 5.13: Effect of vibration test for 50 sec (A), 100 sec (B) and 150 sec (C) on the respiration rate of 'Elsanta' strawberries from the winter cultivation in 2015 after storage at 10^{o}C for between 0-96 hours. Values are the mean from 5 replicates. The S.E. values of treatments with a range of ± 3.72 (winter) values were not shown due to the overlap in error bars producing a confusing graph.

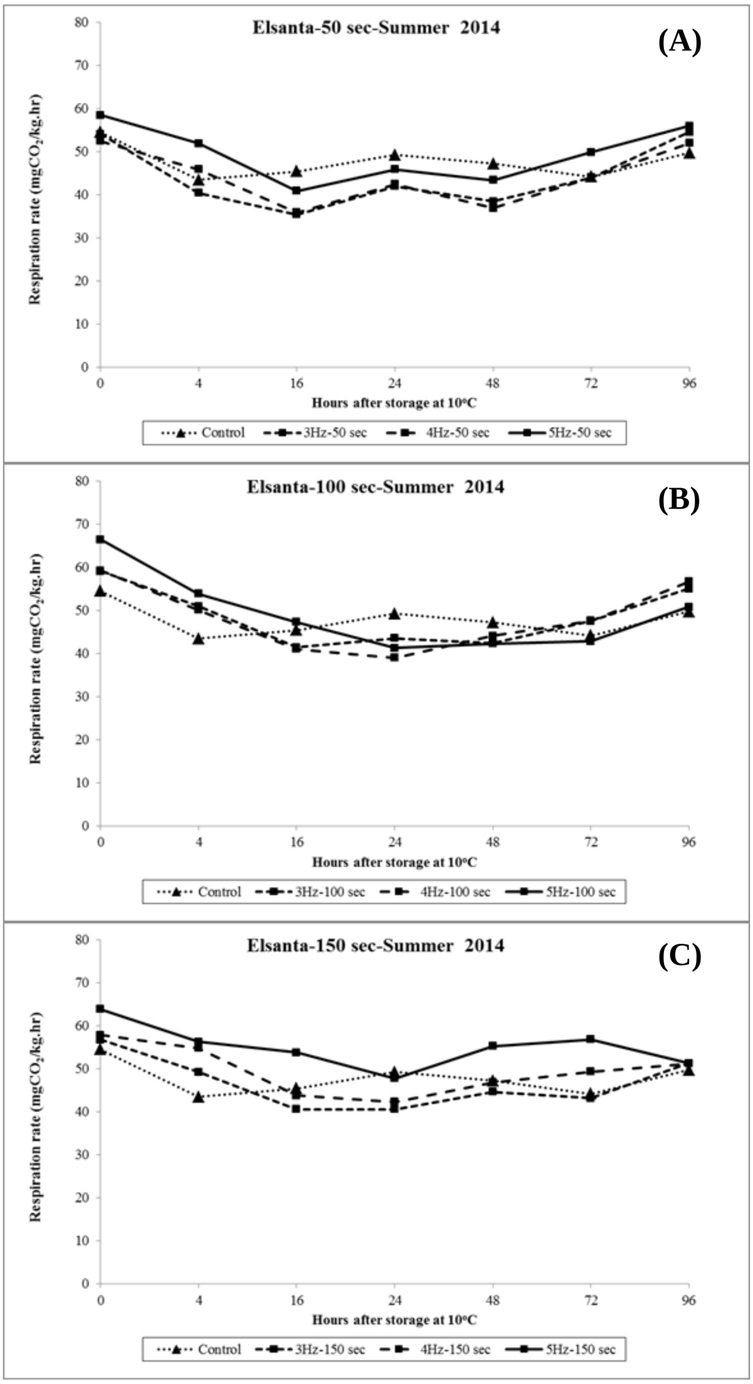
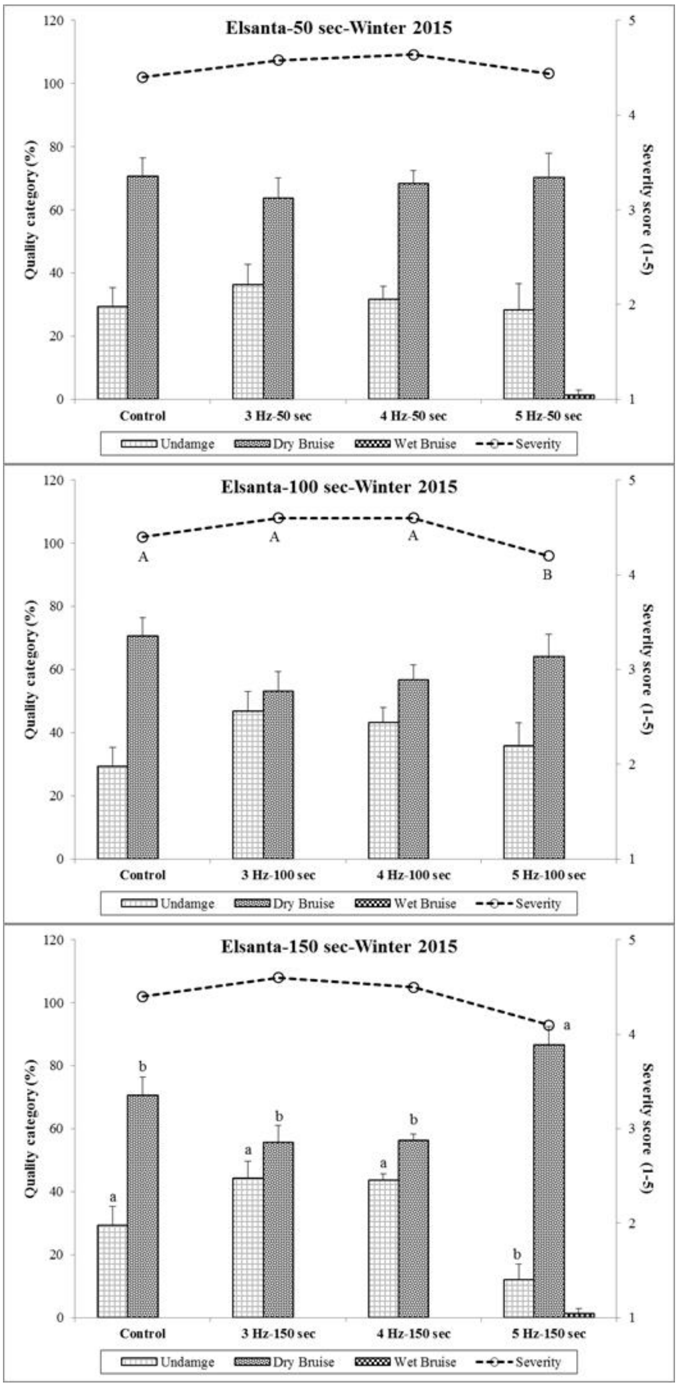


Figure 5.14: Effect of vibration test for 50 sec (A), 100 sec (B) and 150 sec (C) on the respiration rate of 'Elsanta' strawberries from the summer cultivation in 2014 after storage at 10^{o}C for between 0-96 hours. Values are the mean from 3 replicates. The S.E. values of treatments with a range of ± 6.70 (summer) values were not shown due to the overlap in error bars producing a confusing graph.

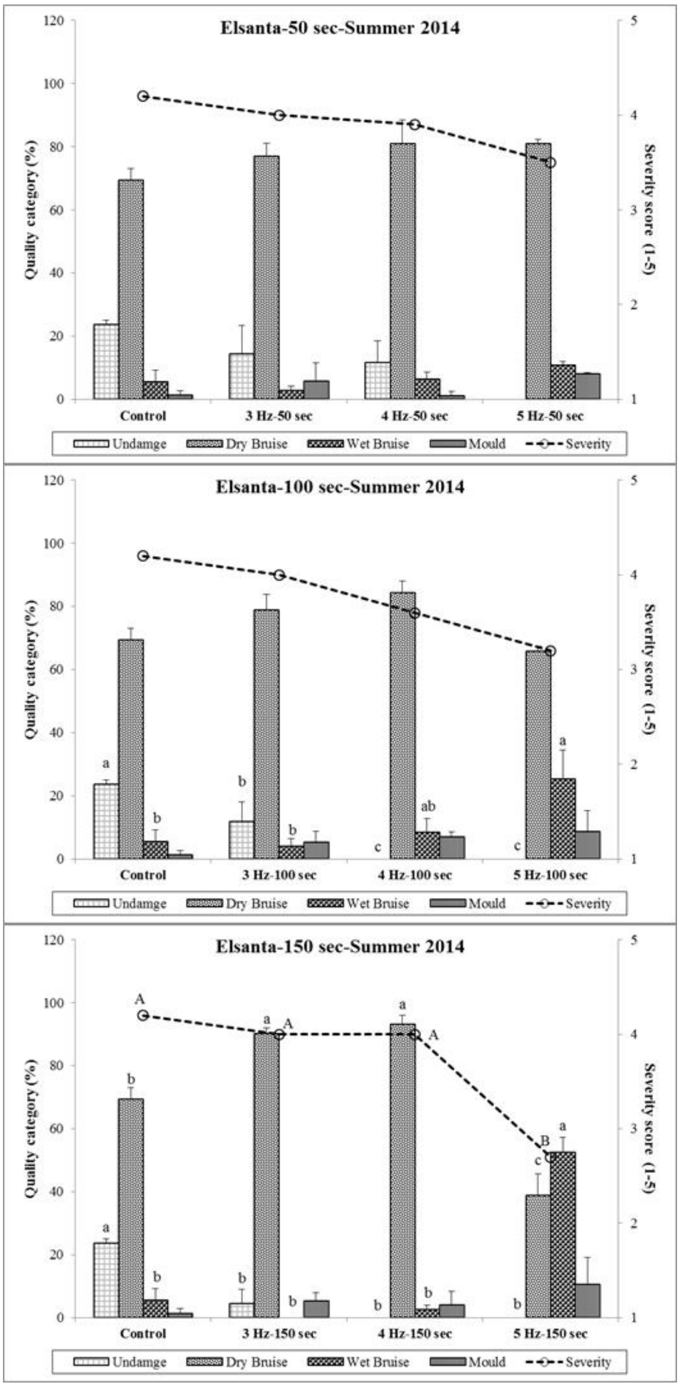


(A)

(B)

(C)

Figure 5.15: Effect of vibration test for 50 sec (A), 100 sec (B) and 150 sec (C) on quality category and severity bruise score of 'Elsanta' strawberries from the winter cultivation in 2015 after storage at 10^{o}C for 96 hours. Different letters in the different frequency levels for DMRT test indicate significant differences at p≤0.05. Values are the mean ±S.E. from 5 replicates.



(A)

(B)

(C)

Figure 5.16: Effect of vibration test for 50 sec (A), 100 sec (B) and 150 sec (C) on quality category and severity bruise score of 'Elsanta' strawberries from the summer cultivation in 2014 after storage at 10°C for 96 hours. Different letters in the different frequency levels for DMRT test indicate significant differences at $p \leq 0.05$. Values are the mean ±S.E. from 3 replicates.

5.5.2 The effect of vibration test on the quality, bruise and respiration rate of 'Sonata' strawberries

5.5.2.1 Percentage of quality category and electrical conductivity of 'Sonata' strawberries

The overall quality category and EC value between 'Sonata' and 'Elsanta' strawberries were compared within two cultivations. Immediately, after vibration for 50 to 150 sec, the result showed that 'Sonata' strawberries had 5-50% of undamaged fruits less than 'Elsanta' cultivar (15-84%) (Figures 5.2, 5.4, 5.17 and 5.19). These findings of damaged fruits related to high levels of wet bruise and EC value in 'Sonata' strawberries, particularly the vibrated Sonata fruits in the summer cultivation (Figure 5.19).

After a vibration test on day 0, the minimum vibrating level (3 Hz) for 50 and 150 sec reduced to around 50% and 20-30% of undamaged fruits, respectively (Figures 5.17 and 5.19), while the maximum frequency at 5 Hz (50 to 150 sec) in the winter cultivation had the similar level of undamaged fruits (<20%) (Figure 5.17). For the vibration duration 50 and 100 sec, dry bruise incidence showed the highest percentage of total fruits with over 40%. The frequency of 5 Hz from 50 to 150 sec gave the highest level of wet bruise ($p \leq 0.05$) (Figures 5.17 and 5.19). The wet bruise damage in the summer cultivation was higher than in the winter cultivation by around 30%, particularly at 5 Hz for 100 and 150 sec (Figure 5.19). A higher level of wet bruise in the summer fruits correlated with a greater EC value to reach 80 µS at the frequency of 4 or 5 Hz for 150 sec (Figure 5.19). The initial EC value of control samples in the summer cultivation was also twice as high as in the winter cultivation (Figures 5.17 and 5.19).

After the entire storage by day 3, the percentage of undamaged fruits in control samples was nearly 30% for the both seasons. The dry bruise incidence at 3 and 4 Hz for 50 and 100 sec increased rapidly to over 80% (winter) and over 60% (summer) (Figures 5.18 and 5.20). The greatest wet bruise of vibrated fruits was noted at 5 Hz for 100 and 150 sec in the summer cultivation ($p \leq 0.05$) (Figures 5.20B-C). A reduction of EC value in the winter cultivation showed a little change when compared to day 0 (Figure 5.18). On the other hand, the greatest EC level was still found in the frequency of 5 Hz for 150 sec, which was twice as great as control (Figure 5.20).

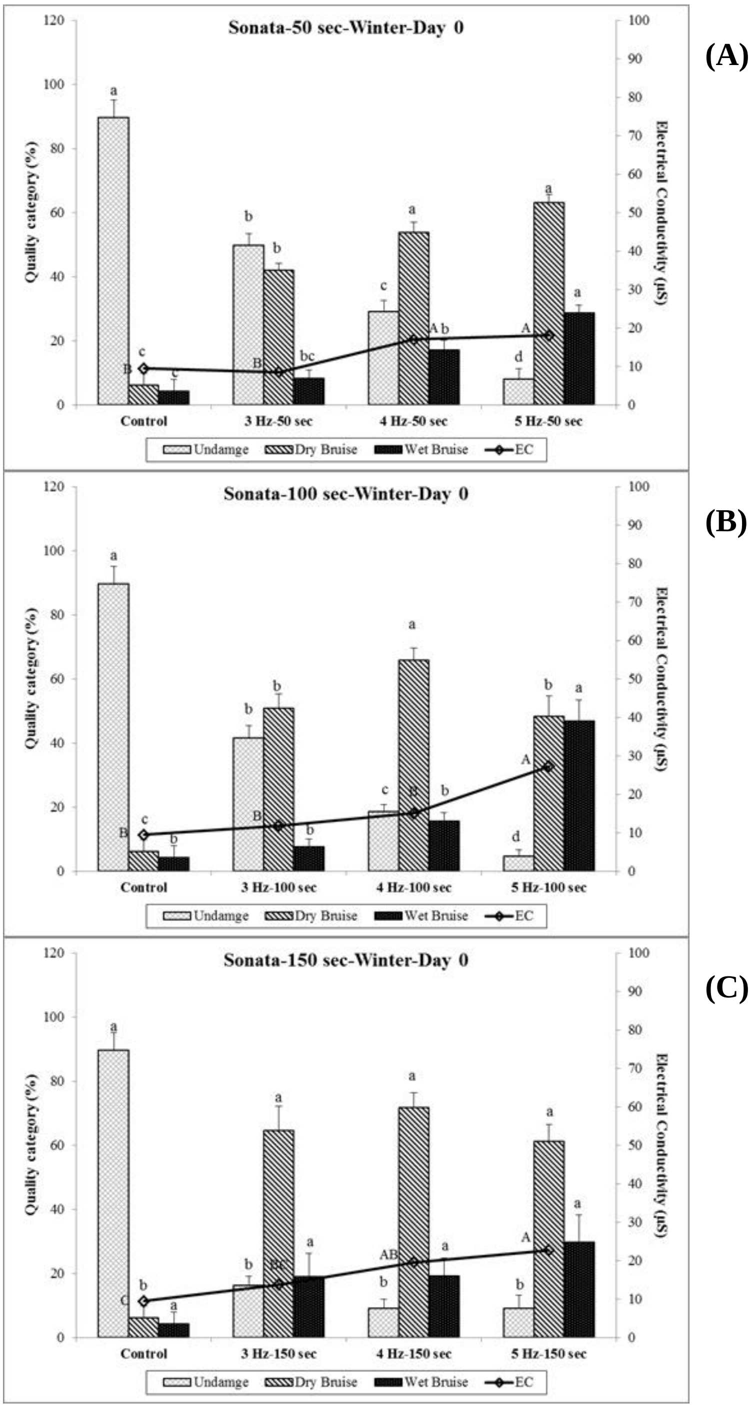
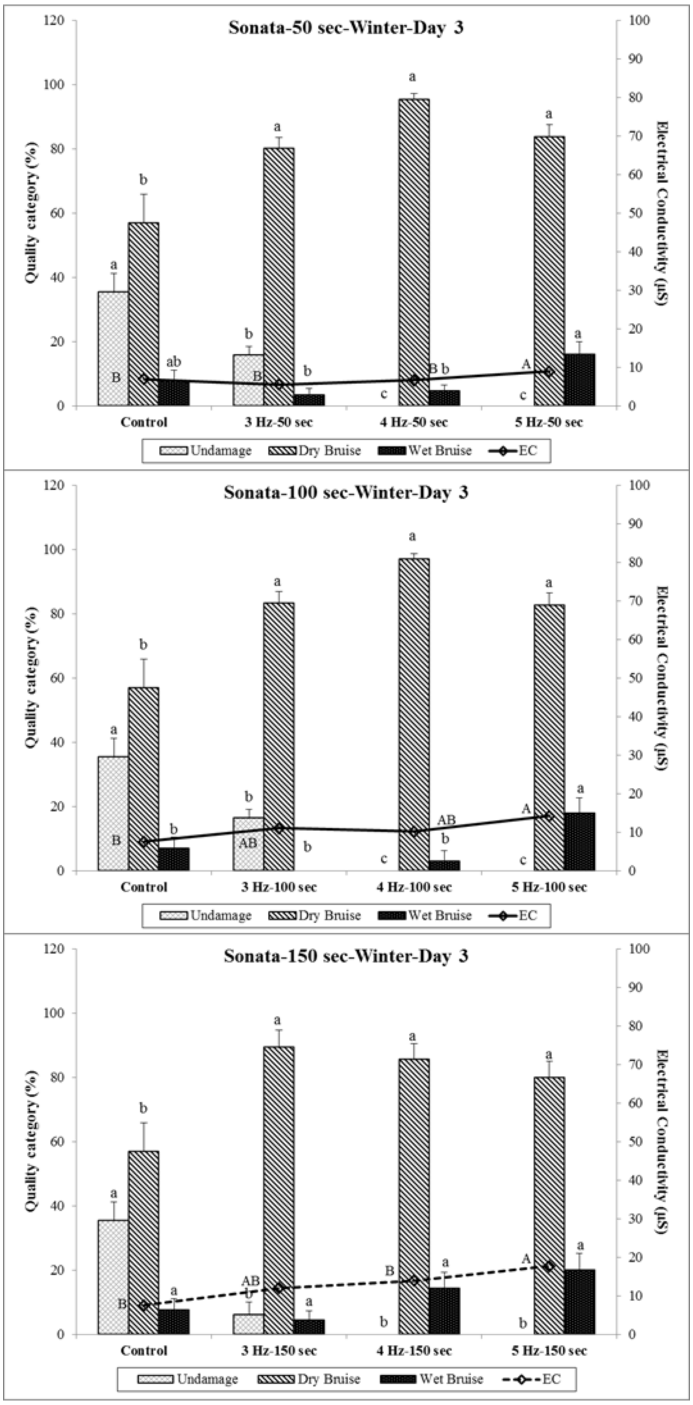


Figure 5.17: Effect of vibration test for 50 sec (A), 100 sec (B) and 150 sec (C) on quality category and electrical conductivity of 'Sonata' strawberries from the winter cultivation at day 0. Different letters in the different frequency levels for DMRT test indicate significant differences at $p \leq 0.05$. Values are the mean ±S.E. from 5 replicates.



(A)

(B)

(C)

Figure 5.18: Effect of vibration test for 50 sec (A), 100 sec (B) and 150 sec (C) on quality category and electrical conductivity of 'Sonata' strawberries from the winter cultivation at day 3. Different letters in the different frequency levels for DMRT test indicate significant differences at p≤0.05. Values are the mean ±S.E. from 5 replicates.

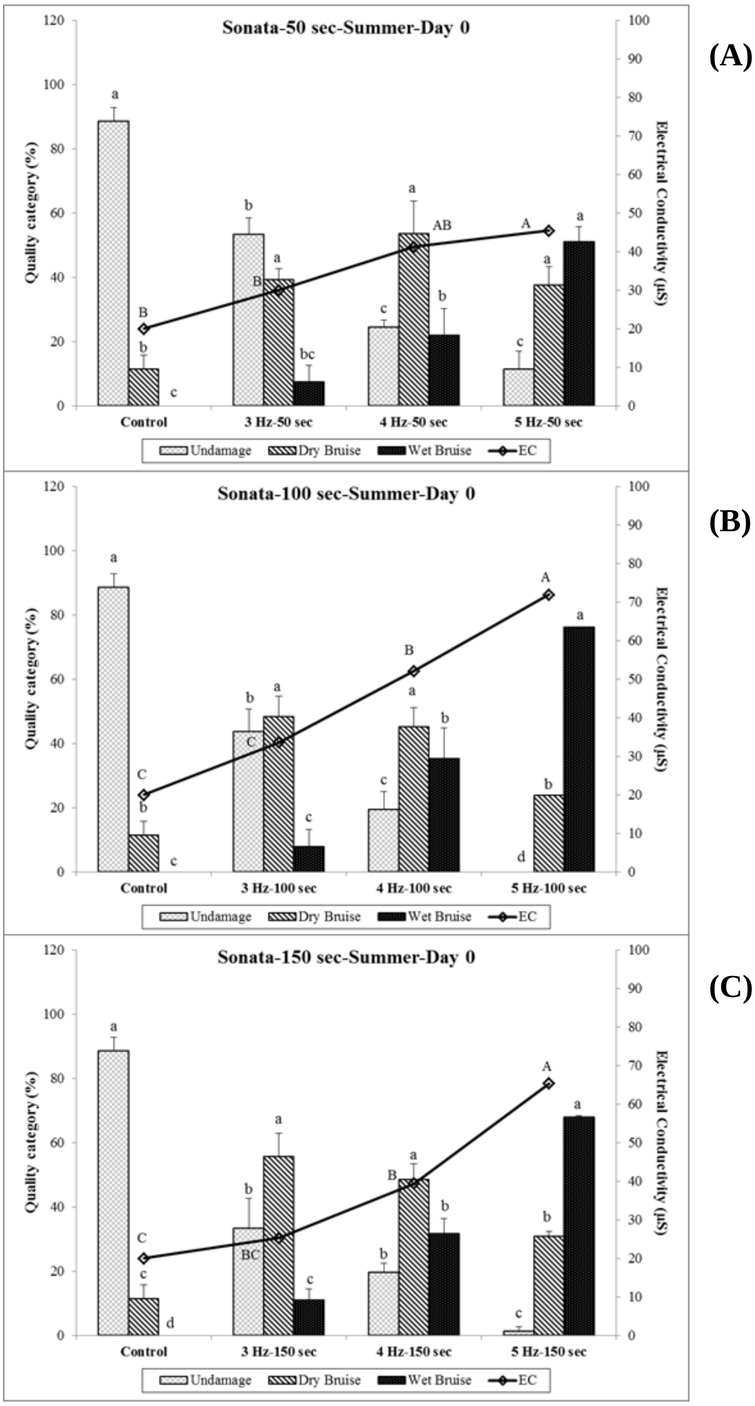


Figure 5.19: Effect of vibration test for 50 sec (A), 100 sec (B) and 150 sec (C) on quality category and electrical conductivity of 'Sonata' strawberries from the summer cultivation at day 0. Different letters in the different frequency levels for DMRT test indicate significant differences at $p \leq 0.05$. Values are the mean ±S.E. from 3 replicate.

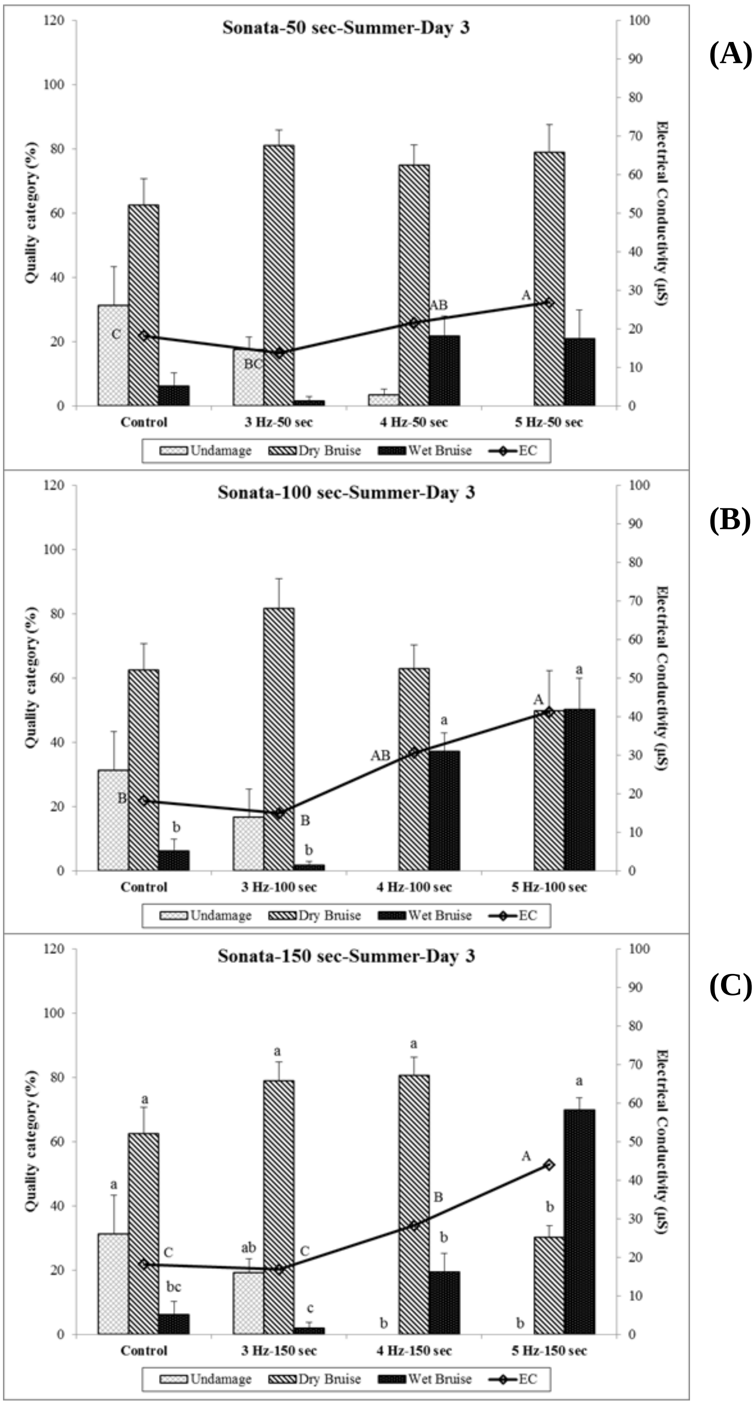


Figure 5.20: Effect of vibration test for 50 sec (A), 100 sec (B) and 150 sec (C) on quality category and electrical conductivity of 'Sonata' strawberries from the summer cultivation at day 3. Different letters in the different frequency levels for DMRT test indicate significant differences at $p \leq 0.05$. Values are the mean ±S.E. from 3 replicates.

5.5.2.2 Fruit weight, firmness (puncture and compression) and severity score of 'Sonata' strawberries

As shown in Tables 5.4 and 5.5, the fruit weight of 'Sonata' in the winter cultivation was approximately 20 g per fruit. However, the summer 'Sonata' fruits were a smaller size than those in the winter production by around 8 g per fruit. There was not a significant difference in fruit weight from the winter production ($p>0.05$). Control samples had a significantly higher compression value than the vibration test fruits both at day 0 and over the entire storage ($p\leq0.05$). Furthermore, there was not a significant difference in compression value with the frequency from 3 to 5 Hz ($p>0.05$). The determination of fruit firmness by a compression test shows a greater difference among the four treatments than by a puncture test. The lowest severity score was found in the frequency of 5 Hz for 150 sec in both seasons ($p\leq0.05$) (Tables 5.4 and 5.5). At the end of storage, the vibration level at 4 and 5 Hz for 150 sec had a severity score below 3 (Table 5.5).

Table 5.4: Effect of vibration test on fruit weight, firmness and severity score of 'Sonata' strawberries from the winter and summer cultivations at day 0.

Treatment	Weight (g)	Puncture (kg)	Compression (kg)	Severity score
		Sonata-Day 0-Winter		
Control	21.35±0.72	0.494±0.008	1.730[a]±0.102	4.8[a]±0.08
3 Hz - 50 sec	20.51±0.54	0.428±0.029	1.427[b]±0.044	4.6[b]±0.06
4 Hz - 50 sec	20.21±0.61	0.422±0.026	1.398[b]±0.058	4.5[b]±0.05
5 Hz - 50 sec	20.48±0.42	0.465±0.025	1.425[b]±0.036	4.3[c]±0.02
Control	21.35±0.72	0.494[ab]±0.008	1.730[a]±0.102	4.8[a]±0.08
3 Hz - 100 sec	20.14±0.62	0.544[a]±0.058	1.470[b]±0.066	4.6[b]±0.04
4 Hz - 100 sec	19.81±0.44	0.390[b]±0.027	1.426[b]±0.056	4.4[b]±0.02
5 Hz - 100 sec	19.34±0.38	0.408[b]±0.028	1.424[b]±0.055	3.9[c]±0.13
Control	21.35[a]±0.72	0.494±0.017	1.730[a]±0.102	4.8[a]±0.08
3 Hz - 150 sec	18.66[b]±0.40	0.491±0.038	1.481[b]±0.061	4.1[b]±0.12
4 Hz - 150 sec	19.23[b]±0.12	0.467±0.015	1.370[b]±0.089	3.9[b]±0.09
5 Hz - 150 sec	19.58[b]±0.36	0.439±0.026	1.365[b]±0.046	3.7[b]±0.17
		Sonata-Day 0-Summer		
Control	20.40[a]±0.28	0.426±0.025	1.786[a]±0.087	4.9[a]±0.03
3 Hz - 50 sec	11.24[b]±0.83	0.354±0.028	1.093[b]±0.052	4.7[a]±0.10
4 Hz - 50 sec	10.76[b]±0.25	0.372±0.040	1.063[b]±0.017	4.3[b]±0.09
5 Hz - 50 sec	12.14[b]±0.93	0.358±0.016	1.065[b]±0.013	3.9[c]±0.10
Control	20.40[a]±0.28	0.426±0.025	1.786[a]±0.087	4.9[a]±0.03
3 Hz - 100 sec	12.12[b]±0.61	0.365±0.004	1.203[b]±0.084	4.6[b]±0.09
4 Hz - 100 sec	11.27[b]±1.09	0.334±0.045	1.041[b]±0.133	4.1[c]±0.14
5 Hz - 100 sec	11.06[b]±0.09	0.321±0.025	1.019[b]±0.042	3.4[d]±0.04
Control	20.40[a]±0.28	0.426[a]±0.025	1.786[a]±0.087	4.9[a]±0.03
3 Hz - 150 sec	11.55[b]±1.13	0.369[ab]±0.010	1.284[b]±0.119	4.5[b]±0.12
4 Hz - 150 sec	12.02[b]±0.94	0.367[ab]±0.012	1.199[b]±0.593	4.1[b]±0.14
5 Hz - 150 sec	12.95[b]±0.31	0.320[b]±0.004	1.160[b]±0.033	3.1[c]±0.05

Means with different letters in the same column at each day and exposure time are significantly different at $p \leq 0.05$. Values are the mean ±S.E. from 5 replicates (winter) and 3 replicates (summer).

Table 5.5: Effect of vibration test on fruit weight, firmness and severity score of 'Sonata' strawberries from the winter and summer cultivations at day 3.

Treatment	Weight (g)	Puncture (kg)	Compression (kg)	Severity score
		Sonata-Day 3-Winter		
Control	19.47±0.59	0.542±0.014	1.696^{a}±0.047	4.1^{a}±0.15
3 Hz - 50 sec	19.00±0.30	0.464±0.034	1.543^{b}±0.054	4.0^{ab}±0.05
4 Hz - 50 sec	19.51±0.34	0.459±0.022	1.464^{b}±0.032	3.7^{bc}±0.05
5 Hz - 50 sec	19.17±0.34	0.456±0.019	1.460^{b}±0.027	3.4^{c}±0.05
Control	19.47±0.59	0.542^{a}±0.014	1.696^{a}±0.047	4.1^{a}±0.15
3 Hz - 100 sec	18.80±0.37	0.491^{ab}±0.017	1.490^{b}±0.038	4.2^{a}±0.10
4 Hz - 100 sec	20.40±0.14	0.436^{b}±0.022	1.494^{b}±0.078	3.4^{b}±0.15
5 Hz - 100 sec	20.20±0.44	0.476^{b}±0.024	1.503^{b}±0.045	2.9^{c}±0.11
Control	19.47±0.59	0.542±0.014	1.696^{a}±0.047	4.1^{a}±0.15
3 Hz - 150 sec	18.92±0.53	0.437±0.013	1.537^{ab}±0.068	3.6^{b}±0.09
4 Hz - 150 sec	19.03±0.29	0.469±0.069	1.483^{b}±0.052	3.3^{b}±0.21
5 Hz - 150 sec	19.70±0.61	0.448±0.030	1.463^{b}±0.054	2.7^{c}±0.17
		Sonata-Day 3-Summer		
Control	18.51^{a}±1.32	0.516±0.017	1.899^{a}±0.093	4.5^{a}±0.15
3 Hz - 50 sec	12.87^{b}±0.59	0.424±0.032	1.305^{b}±0.044	4.2^{a}±0.03
4 Hz - 50 sec	13.19^{b}±0.41	0.402±0.003	1.311^{b}±0.067	3.6^{b}±0.18
5 Hz - 50 sec	13.09^{b}±0.90	0.395±0.063	1.452^{b}±0.098	3.6b±0.16
Control	18.51^{a}±1.32	0.516^{a}±0.017	1.899^{a}±0.093	4.5^{a}±0.15
3 Hz - 100 sec	13.89^{b}±0.39	0.470^{a}±0.003	1.169^{b}±0.023	4.4^{a}±0.09
4 Hz - 100 sec	13.13^{b}±0.36	0.391^{b}±0.010	1.297^{b}±0.106	3.4^{b}±0.12
5 Hz - 100 sec	12.74^{b}±0.76	0.360^{b}±0.038	1.326^{b}±0.053	2.6^{c}±0.43
Control	18.51^{a}±1.32	0.516^{a}±0.017	1.899^{a}±0.093	4.5^{a}±0.15
3 Hz - 150 sec	12.39^{b}±0.29	0.404^{b}±0.028	1.342^{b}±0.046	4.3^{a}±0.03
4 Hz - 150 sec	11.39^{b}±0.45	0.390^{b}±0.062	1.253^{b}±0.128	3.7^{b}±0.15
5 Hz - 150 sec	12.60^{b}±0.12	0.321^{b}±0.009	1.230^{b}±0.058	2.4^{c}±0.27

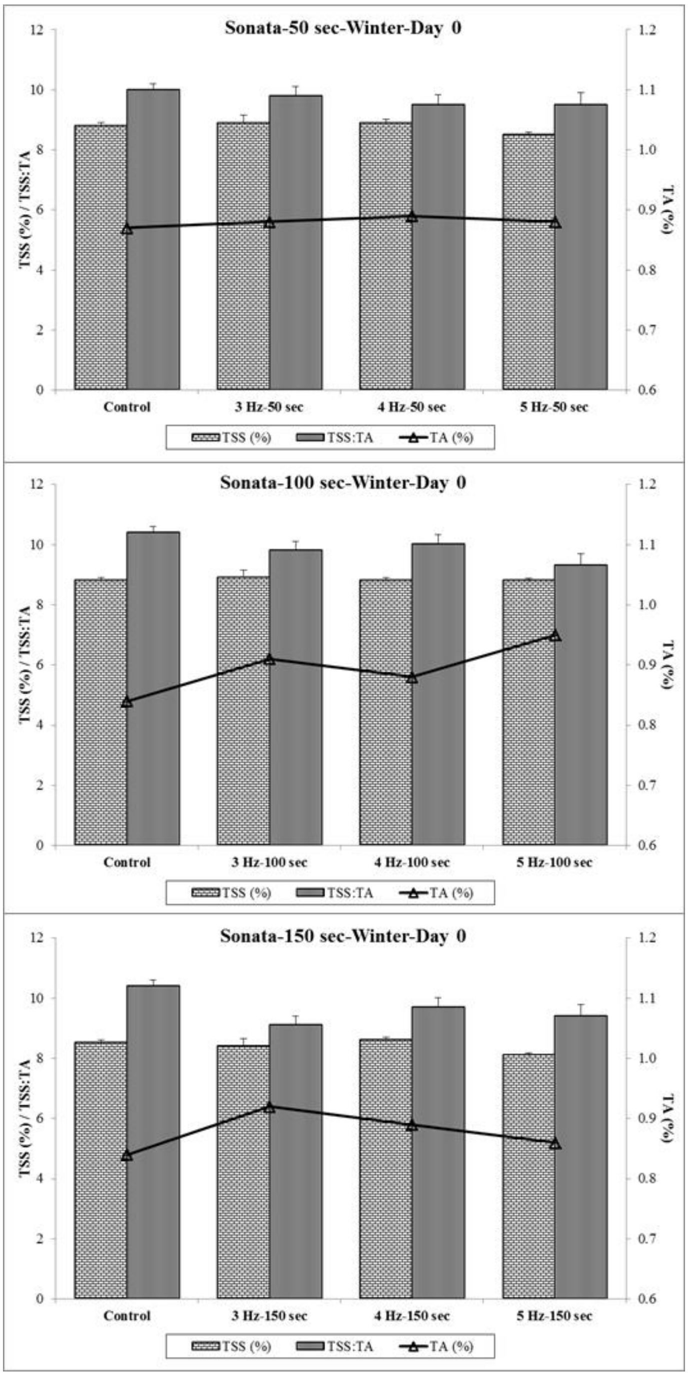
Means with different letters in the same column at each day and exposure time are significantly different at $p \leq 0.05$. Values are the mean ±S.E. from 5 replicates (winter) and 3 replicates (summer).

5.5.2.3 TSS (%), TA (%) and TSS:TA ratio of 'Sonata' strawberries

The TSS content of 'Sonata' strawberries from both cultivations was still over 8% TSS (Figures 5.21-5.24). The summer strawberries (1.0% TA) had a higher TA content than the winter fruits (0.9% TA) (Figures 5.21 and 5.23). The results of TSS and TA contents in 'Sonata' strawberries agreed with those results of 'Elsanta' strawberries, which had their similar levels in both winter and summer cultivations (Figures 5.6-5.9). After harvesting and storage of 'Sonata' fruits, the overall TSS, TA and TSS:TA contents had no significant difference between control treatment and the vibrated fruits, except SS content in the summer production (Figures 5.21-5.23).

5.5.2.4 Fruit surface colour (L*, a*, b*, h*, and C* values) of 'Sonata' strawberries

The fruits vibrated for 100 and 150 sec had a lower h* and a higher a* value (redness) than control fruits ($p \leq 0.05$). These results were also confirmed by the changes of h* and a* values in 'Elsanta' strawberries (Figures 5.11 and 5.12). For the exposure time for 50 sec, there was not a significant difference in fruit surface colour between control samples and vibrated fruits ($p > 0.05$) (Figures 5.25-5.27).



(A)

(B)

(C)

Figure 5.21: Effect of vibration test for 50 sec (A), 100 sec (B) and 150 sec (C) on TSS (%), TA (%) and TSS:TA ratio contents of 'Sonata' strawberries from the winter cultivation at day 0. Different letters in the different frequency levels for DMRT test indicate significant differences at $p \leq 0.05$. Values are the mean ±S.E. from 5 replicates.

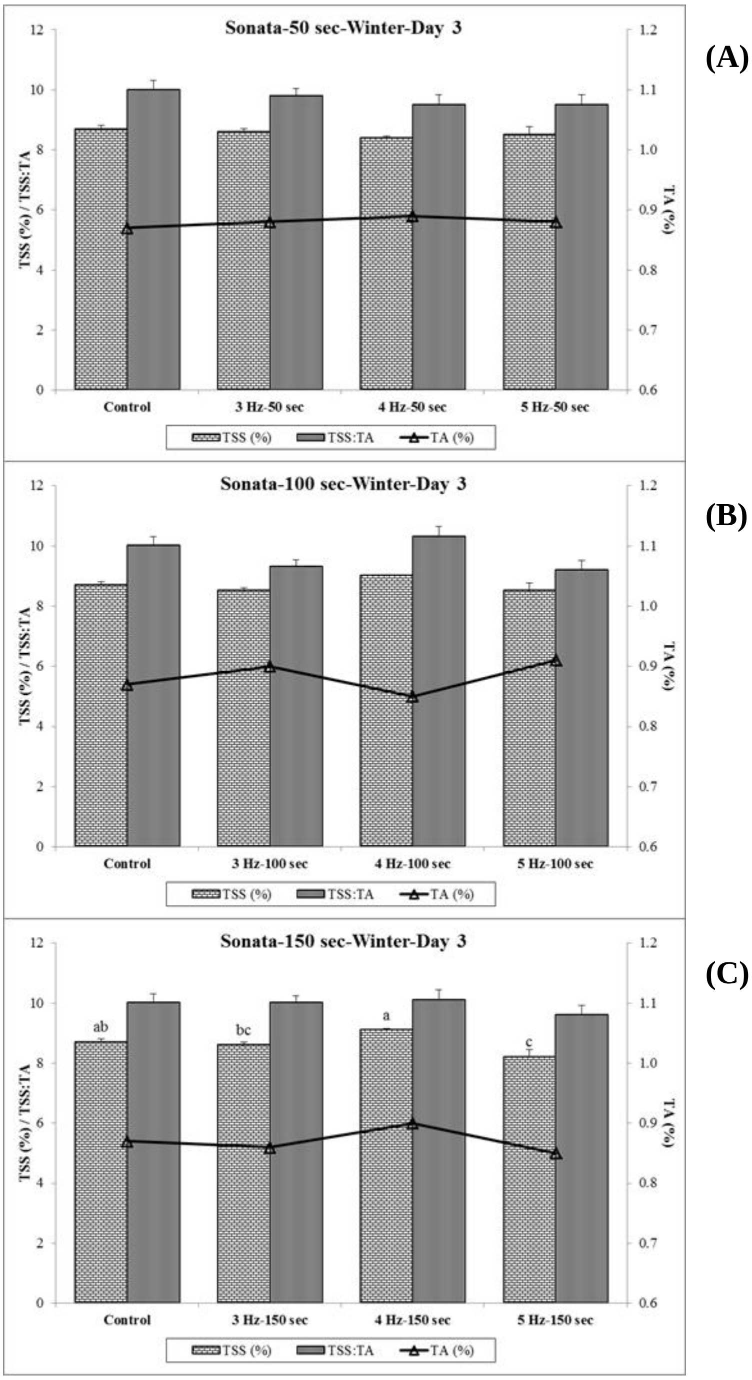
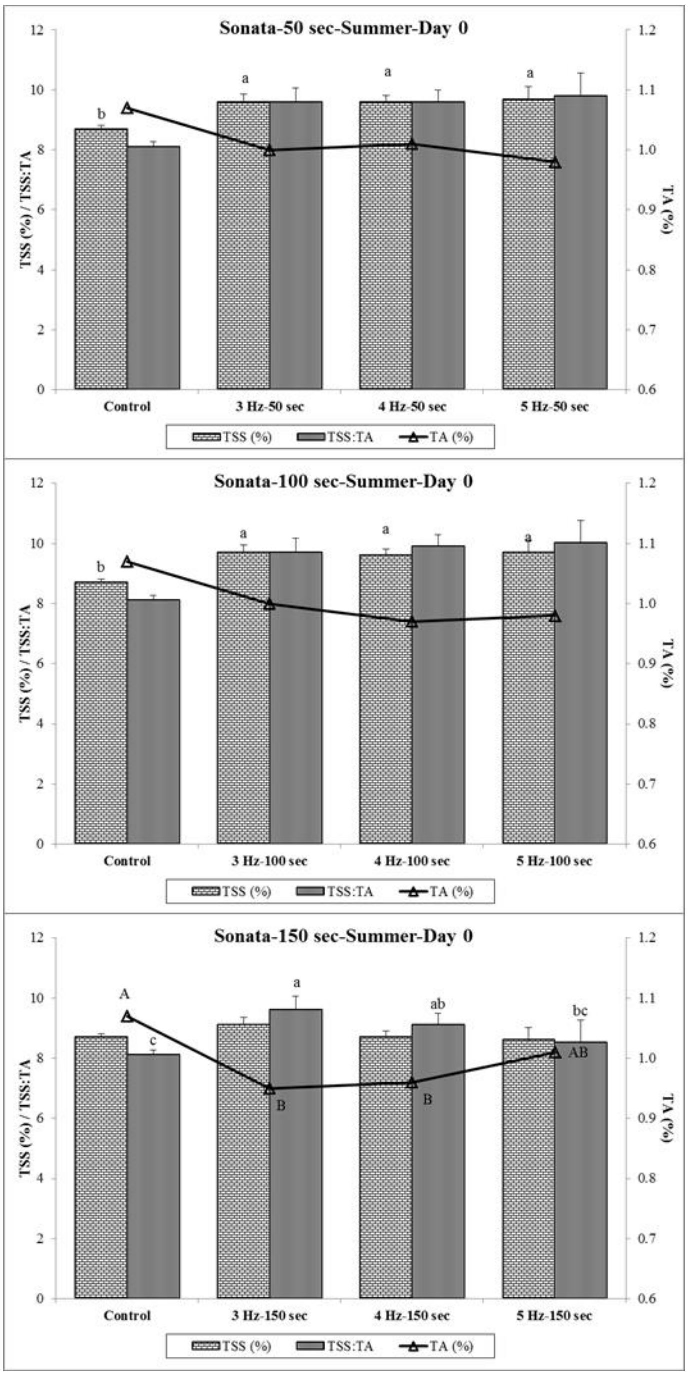


Figure 5.22: Effect of vibration test for 50 sec (A), 100 sec (B) and 150 sec (C) on TSS (%), TA (%) and TSS:TA ratio contents of 'Sonata' strawberries from the winter cultivation at day 3. Different letters in the different frequency levels for DMRT test indicate significant differences at $p \leq 0.05$. Values are the mean ±S.E. from 5 replicates.

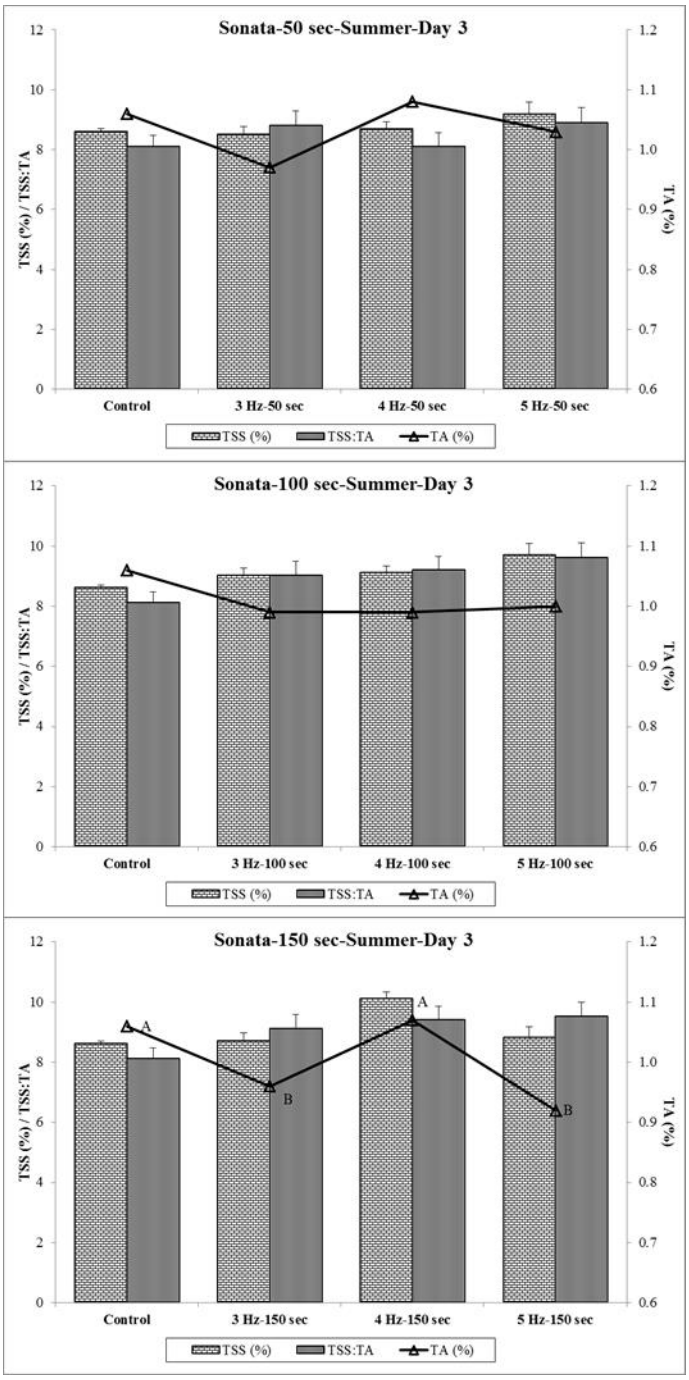


(A)

(B)

(C)

Figure 5.23: Effect of vibration test for 50 sec (A), 100 sec (B) and 150 sec (C) on TSS (%), TA (%) and TSS:TA ratio contents of 'Sonata' strawberries from the summer cultivation at day 0. Different letters in the different frequency levels for DMRT test indicate significant differences at p≤0.05. Values are the mean ±S.E. from 3 replicates.



(A)

(B)

(C)

Figure 5.24: Effect of vibration test for 50 sec (A), 100 sec (B) and 150 sec (C) on TSS (%), TA (%) and TSS:TA ratio contents of 'Sonata' strawberries from the summer cultivation at day 3. Different letters in the different frequency levels for DMRT test indicate significant differences at $p \leq 0.05$. Values are the mean ±S.E. from 3 replicates.

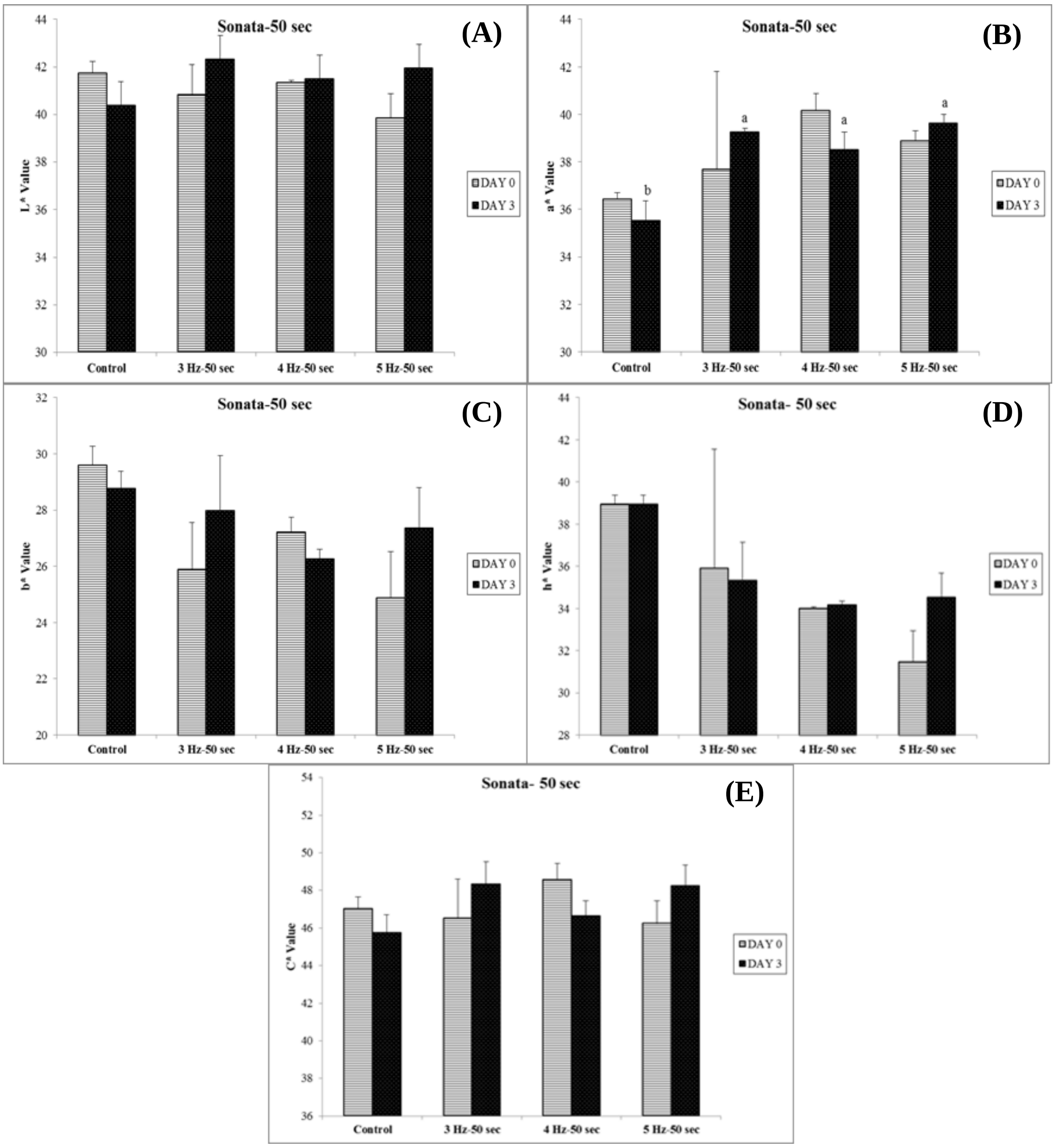


Figure 5.25: Effect of vibration test for 50 sec on the values of L* (A), a* (B), b* (C), h* (D) and C* (E) of 'Sonata' strawberries from the summer cultivation at day 0 and day 3. Different letters in the different frequency levels for DMRT test indicate significant differences at p≤0.05. Values are the mean ±S.E. from 3 replicates.

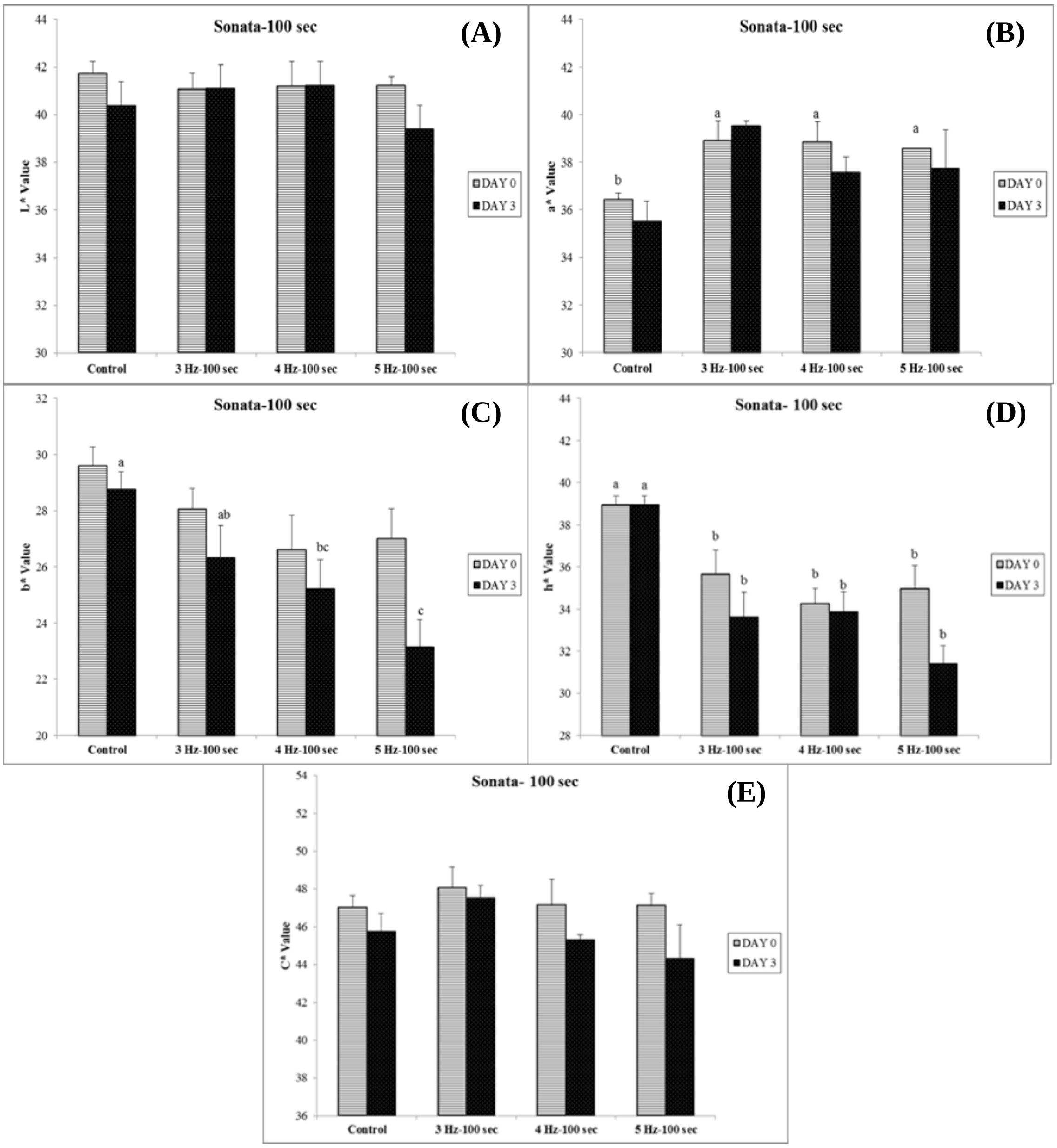


Figure 5.26: Effect of vibration test for 100 sec on the values of L* (A), a* (B), b* (C), h* (D) and C* (E) of 'Sonata' strawberries from the summer cultivation at day 0 and day 3. Different letters in the different frequency levels for DMRT test indicate significant differences at $p \leq 0.05$. Values are the mean ±S.E. from 3 replicates.

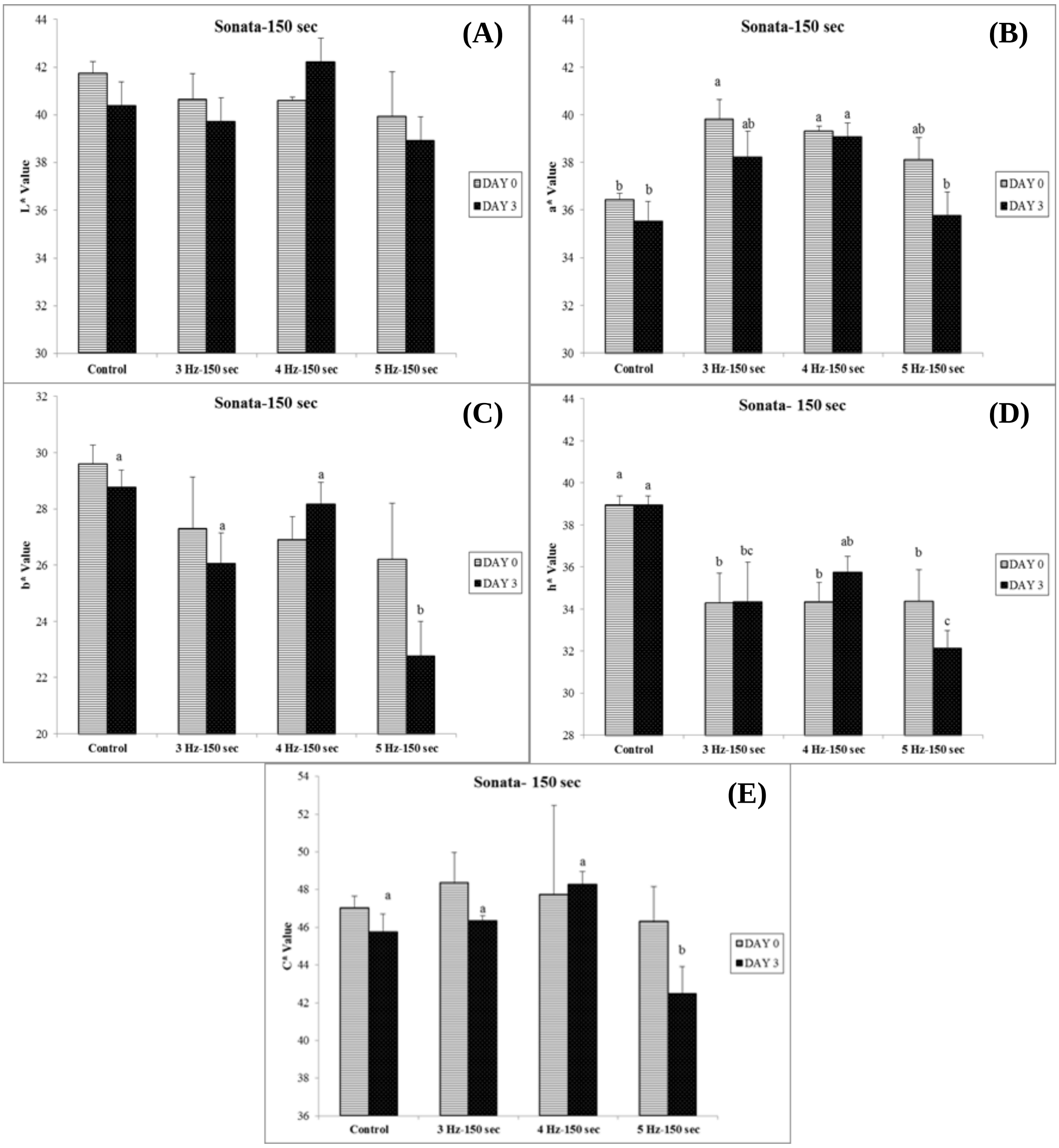


Figure 5.27: Effect of vibration test for 150 sec on the values of L* (A), a* (B), b* (C), h* (D) and C* (E) of 'Sonata' strawberries from the summer cultivation at day 0 and day 3. Different letters in the different frequency levels for DMRT test indicate significant differences at p≤0.05. Values are the mean ±S.E. from 3 replicates.

5.5.2.5 Weight loss (%) of 'Sonata' strawberries

For the entire 3 days storage for, the range of weight loss in the winter cultivation was approximately 2-3%, which was higher than in the summer cultivation (1.5% of weight loss). The vibration level with the different frequencies and exposure times did not directly affect overall weight loss of fruits (Table 5.6), which agreed with those weight loss results of 'Elsanta' cultivar (Table 5.3).

5.5.2.6 Respiration rate, percentage of quality category and severity score of 'Sonata' strawberries after vibration test

Differences in respiration rate and bruise level between 'Elsanta' and 'Sonata' were observed during low storage temperature for 96 hours (4 days). For the winter and summer cultivations, the results showed that the range of respiration rates in 'Elsanta' strawberries (39-66 $mgCO_2$/kg.hr) was a little higher than that of 'Sonata' fruit (32-60 $mgCO_2$/kg.hr) (Figures 5.13-5.14 and 5.28-5.29). Otherwise, in the winter cultivation 2015, 'Elsanta' fruits from the frequency of 5 Hz for 150 sec had a greater percentage of undamaged fruits than 'Sonata' fruits after storage for 4 days (Figures 5.15 and 5.30). In the summer cultivation 2014, the vibrated 'Sonata' fruits at 5 Hz (50, 100 and 150 sec) were observed to have a higher mould incidence (approximate 30%) than those of 'Elsanta' fruits (approximate 20%) (Figures 5.4 and 5.16). Hence, 'Sonata' strawberries had a higher loss than 'Elsanta'strawberries from two cultivations after the end of storage for 96 hours (4 days).

'Sonata' fruits in the winter season (2015) had a lower respiration rate (32-39 $mgCO_2$/kg.hr) than in the summer season (2014) (40-60 $mgCO_2$/kg.hr). Control fruits in the winter and summer cultivations were 32 $mgCO_2$/kg.hr and 46 $mgCO_2$/kg.hr, respectively (Figures 5.28 and 5.29). The vibrated punnet at 5 Hz for 100 and 150 sec had a similar level of respiration rate (37 $mgCO_2$/kg.hr) (Figure 5.28). Furthermore, a high level of respiration rate was also found in the frequency of 5 Hz (50, 100 and 150 sec) in the summer production (Figure 5.29).

At the end of the storage for 96 hours, the undamaged fruits (control) reduced to around 40% of quality category. In the winter cultivation, the fruit damage from dry bruise was a major quality category. All treatments had the severity score at level 4 (Figure 5.30). On the other hand, the undamaged fruits in the summer cultivation decreased to below 20% and there was a mould incidence in all treatments, particularly at 5 Hz (50, 100 and 150 sec). The severity score was a score below 3 for 5 Hz for 100 and 150 sec (Figure 5.31).

Table 5.6: Effect of vibration test on weight loss (%) of 'Sonata' strawberries from the winter and summer cultivations during storage at 10^{o}C for 3 days.

	Weight loss (%)		
Treatment	**Day 1**	**Day 2**	**Day 3**
	Sonata-Winter		
Control	0.82±0.12	1.51^{b}±0.15	1.90±0.29
3 Hz - 50 sec	1.32±0.10	2.07^{a}±0.14	2.78±0.26
4 Hz - 50 sec	0.95±0.09	1.77^{ab}±0.12	2.16±0.23
5 Hz - 50 sec	0.80±0.16	1.35^{b}±0.16	1.76±0.30
Control	0.82±0.12	1.51±0.15	1.90±0.29
3 Hz - 100 sec	1.32±0.12	2.02±0.08	2.68±0.18
4 Hz - 100 sec	1.23±0.08	2.03±0.10	2.48±0.13
5 Hz - 100 sec	1.49±0.09	2.09±0.16	2.56±0.18
Control	0.82±0.12	1.51±0.15	1.90±0.29
3 Hz - 150 sec	1.59±0.20	2.25±0.26	3.05±0.26
4 Hz - 150 sec	1.06±0.36	1.87±0.42	2.36±0.39
5 Hz - 150 sec	0.65±0.03	1.10±0.03	1.75±0.39
	Sonata-Summer		
Control	0.65^{b}±0.09	1.06±0.10	1.33±0.10
3 Hz - 50 sec	0.83^{ab}±0.03	1.19±0.09	1.52±0.11
4 Hz - 50 sec	1.02^{a}±0.14	1.37±0.22	1.74±0.23
5 Hz - 50 sec	1.02^{a}±0.06	1.31±0.08	1.65±0.10
Control	0.65±0.09	1.06±0.10	1.33±0.10
3 Hz - 100 sec	1.02±0.04	1.37±0.04	1.73±0.05
4 Hz - 100 sec	0.92±0.05	1.24±0.14	1.58±0.20
5 Hz - 100 sec	0.79±0.13	1.06±0.21	1.37±0.18
Control	0.65^{b}±0.09	1.06^{b}±0.10	1.33^{b}± 0.10
3 Hz - 150 sec	0.93^{ab}±0.14	1.18^{ab}±0.17	1.50^{ab}±0.21
4 Hz - 150 sec	1.19^{a}±0.21	1.57^{a}±0.20	1.87^{a}±0.18
5 Hz - 150 sec	0.70^{b}±0.12	0.91^{b}±0.12	1.18^{b}±0.12

Means with different letters in the same column at each season are significantly different at p≤0.05. Values are the mean ±S.E. from 5 replicates (winter) and 3 replicates (summer).

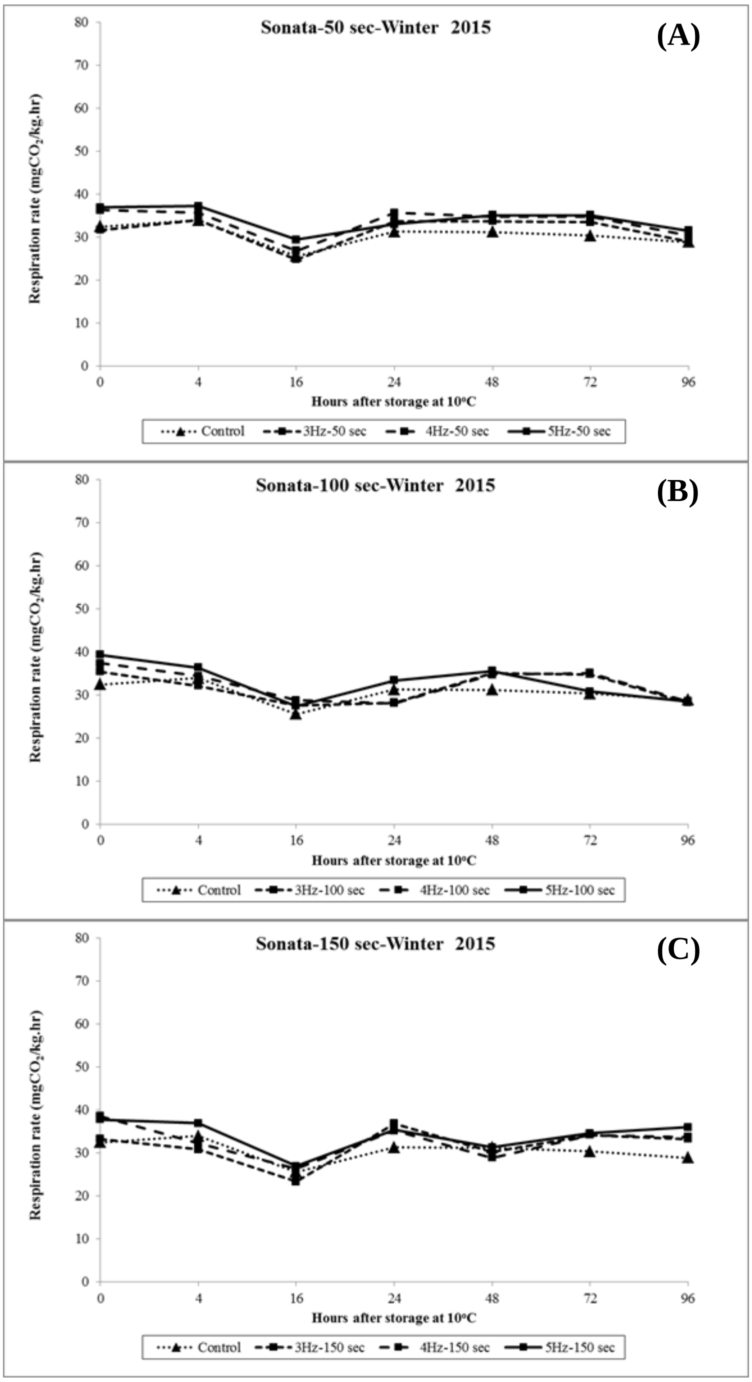


Figure 5.28: Effect of vibration test for 50 sec (A), 100 sec (B) and 150 sec (C) on the respiration rate of 'Sonata' strawberries from the winter cultivation in 2015 after storage at 10^{o}C for between 0-96 hours. Values are the mean from 5 replicates. The S.E. values of treatments with a range of ± 3.53 (winter) values were not shown due to the overlap in error bars producing a confusing graph.

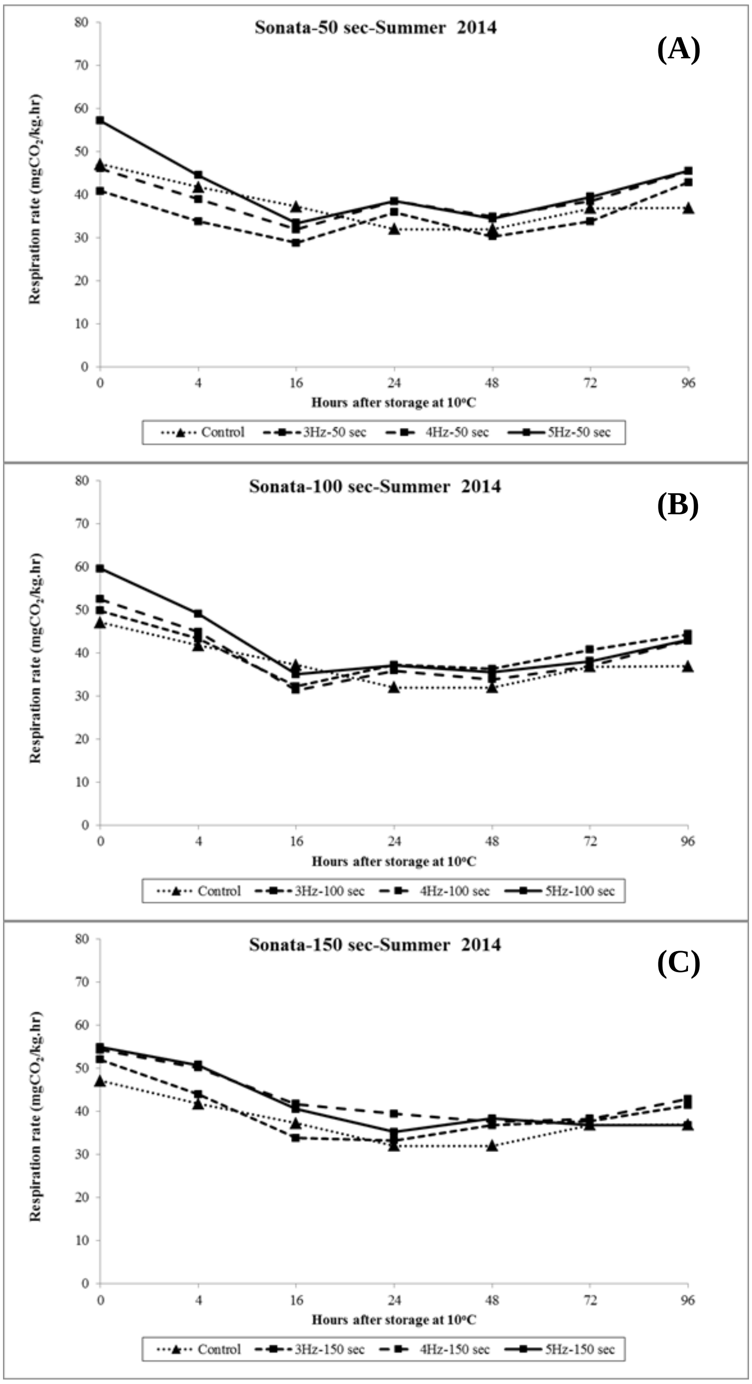


Figure 5.29: Effect of vibration test for 50 sec (A), 100 sec (B) and 150 sec (C) on the respiration rate of 'Sonata' strawberries from the summer cultivation in 2014 after storage at 10^{o}C for between 0-96 hours. Values are the mean from 3 replicates. The S.E. values of treatments with a range of ± 7.49 (summer) values were not shown due to the overlap in error bars producing a confusing graph.

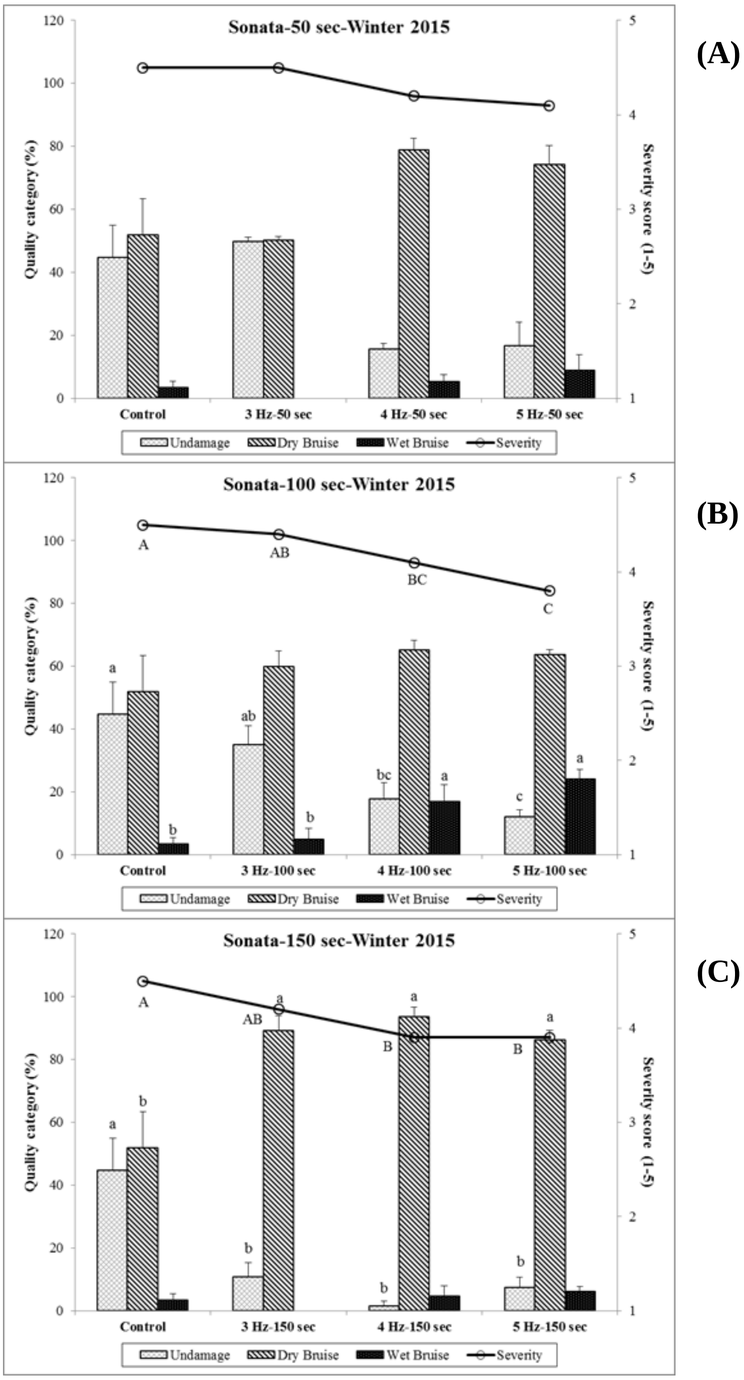


Figure 5.30: Effect of vibration test for 50 sec (A), 100 sec (B) and 150 sec (C) on quality category and severity bruise score of 'Sonata' strawberries from the winter cultivation in 2015 after storage at 10°C for 96 hours. Different letters in the different frequency levels for DMRT test indicate significant differences at p≤0.05. Values are the mean ±S.E. from 5 replicates.

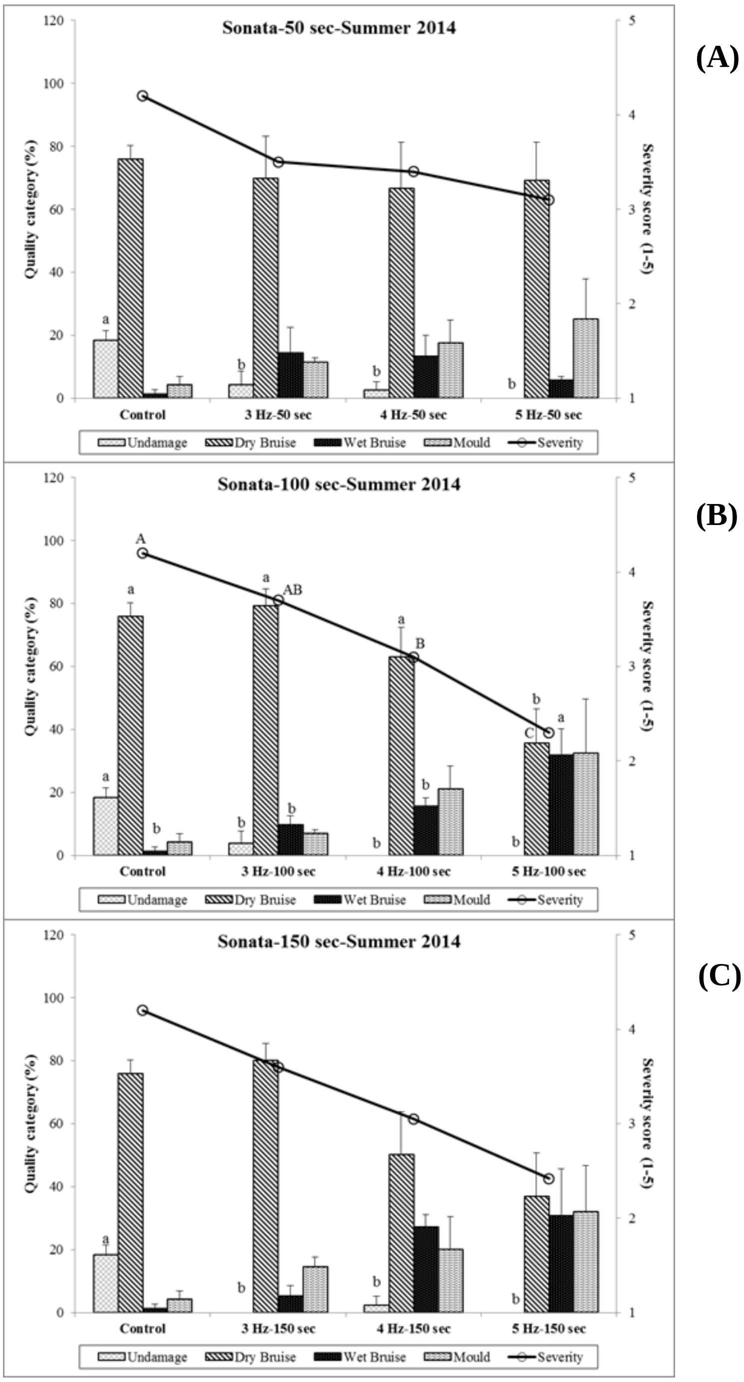


Figure 5.31: Effect of vibration test for 50 sec (A), 100 sec (B) and 150 sec (C) on quality category and severity bruise score of 'Sonata' strawberries from the summer cultivation in 2014 after storage at 10^{o}C for 96 hours. Different letters in the different frequency levels for DMRT test indicate significant differences at $p \leq 0.05$. Values are the mean ±S.E. from 3 replicates.

5.5.3 Correlation coefficient (*r*) between EC value or firmness, and fruit bruise in 'Elsanta' and 'Sonata' strawberry cultivars after vibration test

The data analysis in each cultivation was obtained from all samples for the three frequency levels (3, 4 and 5 Hz) and three periods of exposure time (50, 100 and 150 sec), including control. The evaluations of fruit quality by the selected physical properties (EC, fruit firmness, respiration rate) was analysed to find the correlation coefficient (*r*) with visual assessment (bruise damages and fruit severity). The data analysis was presented for each cultivar, cultivation and period of storage. For a bruise indicator from the vibration test, there is a strong relationship between physical properties and vibration bruise (Tables 5.7 and 5.8). As shown in Table 5.9, the highest correlation correlation coefficient (*r*) value indicates the best predictor of strawberry bruise from vibration test after cool storage for 3 days.

5.5.3.1 The correlation between physical properties (EC, firmness and respiration rate) and fruit bruise of 'Elasata' strawberries after vibration test and storage

As shown in Table 5.7, the results of correlation coefficient (*r*) from 'Elsanta' strawberries for the winter and summer cultivations were examined on day 0 and day 3. The EC value, fruit firmness and respiration rate had a high relationship with wet bruise as compared to dry bruise, particularly for the summer cultivation. For example, the EC evaluation of the summer cultivation ($r > 0.800$) had a significantly higher correlation than the puncture and compression tests ($p \le 0.01$). Therefore, the EC technique had a greater accuracy than the fruit firmness tests for evaluating strawberry bruise from vibration test. Both the puncture and compression tests gave a similar level of the correlation coefficient in wet bruise incidence. In addition, the EC value had a significant relationship with a severity score in the summer production ($p \le 0.01$).

5.5.3.2 The correlation between physical properties (EC, firmness and respiration rate) and fruit bruise of 'Sonata' strawberries after vibration test and storage

The EC method was significantly related to wet bruise as compared to dry bruise ($p \le 0.01$). In wet bruise incidence, the correlation coefficient (*r*) of the EC method still was a significantly higher value than the fruit firmness in both cultivations and periods of storage ($p \leq 0.01$). The severity score by the visual assessment of individual fruit also significantly related to the EC method ($p \leq 0.01$) (Table 5.8). These above results of 'Sonata' strawberries agreed with those of 'Elsanta' strawberries (Table 5.7). There was a significantly higher firmness in control samples of 'Sonata' cultivar in the summer production (Tables 5.4 and 5.5), and the fruit weight had a significant relationship with puncture and compression tests ($p \leq 0.01$) (Table 5.8). Therefore, a bigger fruit gave a higher fruit firmness.

Table 5.7: The correlation coefficient (*r*) between bruise determinations (EC, firmness and respiration rate values) and fruit bruise of 'Elsanta' strawberries on day 0 and day 3 after vibration test.

Properties	**Dry bruise**	**Wet bruise**	**Severity score**	**Dry bruise**	**Wet bruise**	**Severity score**
	Elsanta-Winter cultivation Day 0			***Elsanta-Summer cultivation Day 0***		
EC	0.649**	0.482**	-0.685**	-0.210	0.800**	-0.715**
Puncture	-0.115	-0.033	0.073	-0.054	-0.399	0.362
Compression	-0.083	-0.139	0.200	-0.238	-0.373	0.349
Respiration rate	0.586**	0.253	-0.588**	-0.264	0.612**	-0.576**
	Elsanta-Winter cultivation Day 3			***Elsanta-Summer cultivation Day 3***		
EC	-0.134	0.882**	-0.611**	-0.605**	0.893**	-0.475**
Puncture	-0.125	-0.397**	0.250	0.310	-0.439	0.278
Compression	-0.325	-0.254	0.378**	0.226	-0.475	0.349
Respiration rate	0.058	0.262	-0.057	-0.313	0.570	-0.265

** Pearson's correlation is significant at 1% level in the winter cultivation (n=50) and the summer cultivation (n=30).

Table 5.8: The correlation coefficient (*r*) between bruise determinations (EC, firmness and respiration rate values) and fruit bruise of 'Sonata' strawberries on day 0 and day 3 after vibration test.

Properties	Dry bruise	Wet bruise	Severity score	Dry bruise	Wet bruise	Severity score	Fruit weight
	Sonata-Winter cultivation			***Sonata-Summer cultivation***			
	Day 0			***Day 0***			
EC	0.255	0.732**	-0.791**	-0.119	-0.822**	0.805**	-0.263
Puncture	0.037	-0.344	0.207	0.061	-0.585**	0.560**	0.503**
Compression	-0.444**	-0.340	0.402**	-0.349	-0.459**	0.471**	0.803*
Respiration rate	0.328	0.342	-0.329	0.161	0.529**	-0.561**	-0.007
	Sonata-Winter cultivation			***Sonata-Summer cultivation***			
	Day 3			***Day 3***			
EC	0.044	0.553**	-0.603**	-0.708**	-0.928**	0.897**	-0.180
Puncture	-0.321	0.060	0.251	0.312	-0.628**	-0.680**	0.611**
Compression	-0.293	-0.172	0.310	-0.140	-0.226	0.291	0.731**
Respiration rate	0.195	0.057	-0.096	-0.028	0.139	-0.316	-0.059

** Pearson's correlation is significant at 1% level in the winter cultivation (n=50) and the summer cultivation (n=30).

5.5.3.3 The correlation between physical properties (EC, firmness and respiration rate) immediately after vibration test on day 0 and fruit bruise of 'Elsanta' and 'Sonata' strawberries and after storage on day 3

As shown in Table 5.9, the EC method on day 0 showed a significantly greater correlation with wet bruise and a severity score on day 3 than firmness tests and respiration rate measurement. Also, this result of the EC method from vibration test agreed with the consistent result of the EC method from impact test. However, the EC method of vibration test had lower correlation coefficient values (*r*) for the impact test (Table 4.7). From this strong correlation coefficient (*r*) results of impact and vibration bruises on day 3, the EC method is suggested for use as the potentially best bruise indicator and predictor of bruised 'Elsanta' and 'Sonata' strawberries for both impact and vibration damage.

Table 5.9: The correlation coefficient (*r*) between bruise determinations (EC value, firmness and respiration rate value) on day 0 after vibration test and fruit bruise of 'Elsanta' and 'Sonata' strawberries on day 3 after storage.

Properties (Day 0)	**Dry bruise**	**Wet bruise**	**Severity score**	**Dry bruise**	**Wet bruise**	**Severity score**
	Elsanta-Winter cultivation Day 3			***Elsanta-Summer cultivation Day 3***		
EC	0.305	0.455**	-0.518**	-0.008	0.412	-0.561**
Puncture	-0.037	-0.112	0.042	-0.019	0.335	0.529**
Compression	0.069	0.082	0.086	0.177	0.348	0.305
Respiration rate	0.012	0.482**	-0.274	-0.155	0.301	-0.303
	Sonata-Winter cultivation Day 3			***Sonata-Summer cultivation Day 3***		
EC	0.172	0.465**	-0.567**	-0.431	0.721**	-0.772**
Puncture	-0.193	-0.012	0.270	0.174	-0.445	0.518**
Compression	-0.530	0.092	0.210	-0.167	-0.261	0.405
Respiration rate	0.242	0.206	-0.363	-0.213	0.465**	-0.508**

** Pearson's correlation is significant at 1% level in the winter cultivation (n=50) and and the summer cultivation (n=30).

5.6 DISCUSSION

The effect of frequency and exposure time on the quality, bruise and respiration rate of 'Elsanta' and 'Sonata' strawberries

5.6.1 Fruit bruise, fruit shape and severity score

Strawberries were found to be less susceptible to vibration damage than impact and compression damages (Smith *et al.*, 2004; Ferreira *et al.*, 2008). Fruit movement inside packages during transport probably causes more severe damage than simple compression. The causes of vibration between fruit are more complicated than impacts (Knee and Miller, 2002). In the current study, the wet bruise was strongly affected by the test method and season cultivation. Commercially, the spring cultivation is a common period for the British strawberries for summer consumption. In the winter cultivation, immediately after testing for both cultivars, the overall wet bruise of the vibration test (5-50%) (Figures 5.2-5.3 and 5.17- 5.18) was less than from those results of the impact test (15-60% wet bruise) (Figures 4.2, 4.9). The summer cultivation (5-80%) also produced a higher wet bruise level than the winter cultivation (5-50%) (Figures 5.2-5.5 and 5.17-5.20). These results agreed with those results of the impact test and also showed high propotion of undamaged fruits and wet bruise levels in the summer cultivation (Figures 4.3 and 4.10).

As mentioned previously in the effect of fruit shape on bruised fruit were described and discussed in terms of curvature radius as the result in a higher impact damage (section 4.6.2.2). For vibration damage, the bruised peaches and discoloration at shoulder contact was also affected by a small radius of curvature (Vergano *et al.*, 1991). After the impact test, there was not a difference in bruised damage between 'Elsanta' and 'Sonata' cultivars. The bruise damage from the impact test may not be affected by fruit shape. Conversely, after vibration test and low temperature storage, 'Sonata' cultivar had a higher susceptibility to bruise damage from the vibration test than the 'Elsanta' cultivar. The results showed that the overall wet bruise or dry bruise in 'Sonata' cutivar from both cultivations was significantly higher than that in 'Elsanta' cultivar (data not shown). Also, the overall severity score for both cultivars was a score over 3, except 'Sonata' cultivar at a frequency of 5 Hz (100 and 150 sec) in the summer cultivation (Tables 5.1-5.2 and 5.4-5.5). The differences between susceptibility to bruise for 'Elsanta' and 'Sonata' cultivars were found in wet bruise and the fruit severity that may be different in fruit shape or cell membrane integrity. The observation of fruit shape was examined from strawberries in the winter cultivation (2015) (Appendix 3) and from visual assessment in the summer cultivation (data not shown). Even the fruit shape of 'Sonata' cultivar was roughly presented as a rounder shape than 'Elsanta', which showed a lower fruit shape index and a higher minor lateral diameter. 'Sonata' fruit could have a small radius of curvature. Therefore, a possibility of susceptible bruising of 'Sonata' fruits may not involve fruit shape, but may relate to cell membrane integrity, which is correlated to a higher EC value of 'Sonata cultivar (Figures 5.17-5.20).

In the current study, the critical condition for strawberry damage was not only the effect of frequency and the exposure time, but also varied for cultivar and growing season. On day 0, the reduction of over 50% undamaged fruits in 'Elsanta' and 'Sonata' cultivars started from 5 Hz for 100 sec in the winter cultivation, and from 5 Hz for 50 sec in the summer cultivation (Figures 5.2B-C, 5.4A, 5.17B-C and 5.19A). In both cultivars, a frequency of 5 Hz (1.1 *g*) gave the highest wet bruise levels in summer cultivation (40-80%) (Figures 5.4- 5.5 and 5.19-5.20) and in the winter cultivation (5-50%) (Figures 5.2-5.3 and 5.17-5.18). In the winter season, the vibration levels from all frequencies and exposure times did not have an effect on wet bruise of 'Elsanta' cultivar, except 5 Hz on day 0 (Figure 5.2). In contrast, a frequency of 5 Hz (1.1 *g*) gave the highest wet bruise of 'Sonata' cultivar for three exposure times (50, 100 and 150 sec) (Figure 5.17). In these results, therefore, the overall frequency of 5 Hz (1.1 *g*) for 150 sec was a highly important condition to reach the minimum undamaged fruits and the maximum wet bruise.

There is a large volume of published studies describing the simulated vibration to strawberry bruise. There has been a wide range of vibration conditions used for strawberry tests with a frequency of 5-10 Hz (0.6 to 1.6 *g*) for 40-3600 sec (Fischer *et al.*, 1992; Jiang *et al.*, 2001; Nakamura *et al.*, 2007b; Nakamura *et al.*, 2008). Fischer *et al.* (1992) reported that the highest damage on ‘Selva’ strawberries was found at the frequency of 5-10 Hz (0.6 *g*) for 600 sec. In the case of an actual transport to strawberry damage, this vibration condition has a lower acceleration level (0.02-0.18 *g*) than for simulated vibration, while the estimated frequencies (3.5-13.5 Hz) were similar to the simulated vibration (Kojima *et al*,. 1999). Mao *et al.* (1995) found that fig vibrated fruits at 1 *g* gave a higher EC than no vibration or vibration at 2 *g*. As mentioned in the literature of both simulated and actual vibrations, the vibration condition at 5 Hz (1.1 *g*) for 150 sec in this vibration study was in the same range of previous studies to cause bruising strawberry in simulated vibration. The current findings confirmed those of Nakamura *et al.* (2008), who found that there was a strong relationship between an acceleration level (*g*) and damage of strawberry fruits. Also, Jiang *et al.* (2001) reported that the vibration level at 5 Hz with the range of acceleration level (1.2 to 1.6 *g*) showed a significant correlation with the strawberry damage. The vibration level was monitored in a refrigerated truck and semi-trailer during food delivery on the road transport in the UK. The vibration results will be reported in the next chapter (section 6.5).

Additionally, the direction of vibration and packing also related to vibration level during road transport. Nakamura *et al.* (2007b) found that a tidy arrangement for strawberry packing caused fewer bruised strawberries from the vertical vibration (Z-axis) than longitudinal vibration (Y-axis) after the simulated vibration test. The strawberries (24-26 fruits) were packed in two layers with three rows per layer. However, several found that the vertical vibration (Z-axis) represented the highest vibration level during monitoring levels in vehicles such as truck, van and rail (Chonhenchob *et al.*, 2009, 2010, 2012; Lu *et al.*, 2010a; Rissi *et al.*, 2008). In the current study and the commercial packing of the British strawberries, these severe bruise of strawberries may be increased by the vertical vibration due to untidy packing.

From a personal investigation, the packing size of the British strawberry punnets was observed in four supermarkets during the summer harvesting. The most common size for packing was 400 g per punnet, which was a vented PET package (105 x 170 x 80 mm) with a cushion (small piece of bobble sheet). In particular, the inserted cushion within a punnet should protect compression damage at the bottom fruits. A larger package with an increase of punnet height (20 mm) was used as a commercial packing of strawberries with the same length and width of punnet in the current study (data not shown). Therefore, a number of strawberries pile up inside this punnet, which may cause fruit-to-fruit damage. Knee and Miller (2002) reported that long periods of stress on fruit structures result in unrecoverable original dimensions. The probability of one cell failure starts with a reduction of energy in the strained tissue and extends to the other cell failures. An increase of cell failure with time causes failure at lower energies rather than failure in impacts. Commonly, postharvest life of strawberries is 4-8 days for domestic produce and 8-14 days for imported produce (Terry *et al.*, 2011). Thus the number of bruised strawberries should increase and a more severe damage after storage may be found due to an increase of another impact damage (fruit-to fruit damage) from farm to supermarket. Blahivec *et al.* (2002) reported that bruise volume, loading energy and absorbed energy increased with an increasing level of loading. A further study with more focus on fruit-to-fruit damage is therefore suggested to study the changes of strawberry bruise after testing and storage for shelf-life.

5.6.2 Electrical conductivity (EC)

An increase of electrolyte leakage has been used as a good indication of cell membrane integrity from chilling injury symptom, fruit ripening and mechanical damage, which is related to quality of fresh produce (Saltveit, 2002; Ahmed *et al.*, 2010; Deng *et al.*, 2005; Jiang *et al.*, 2001; Milczarek *et al.*, 2009; Zhou *et al.*, 2007). The EC values from undamaged fruits and fruit bruises in the summer cultivation were three times higher than those in the winter cultivation (Figures 5.2-5.5 and 5.17-5.20). Castro *et al*. (2004) reported that an ohmic heating of strawberry pulp to 100^{o}C changed a linear relationship with an increased electrical conductivity. As regards strawberry bruise in this vibration study, the highest EC values of the strawberry bruise showed at a frequency of 5 Hz (1.1 *g*) for 50, 100 and 150 sec. It should be noted that the EC method is more efficient to distinguish between control samples and vibrated fruits, particularly at a frequency of 5 Hz (1.1 *g*) (Figures 5.2-5.5 and 5.17-5.20).

A higher electrical conductivity (EC) from the strawberry bruise showed on day 0 and gradually declined after the end of storage (day 3), which related to an increase of dry bruise strawberries (Figures 5.2-5.5 and 5.17-5.20). These results of the vibration test agreed with the changes of EC values from the impact test (Figures 4.2-4.3 and 4.9-4.10). Jiang *et al.* (2001) also reported that the EC value of vibrated strawberries reduced throughout the end of storage at 25^{o}C for 2 days due to the possibility of wound healing of the fruit. In wounded tuber, root and bulb crops, Cantwell and Kasmire (2002) reported that their wound healing conditions are generally higher temperature (15-45^{o}C) with a range of relative humidity (60-100%), which can reduce water loss and decay. In fresh fruit, the wounded cucumber was 26^{o}C and 85-90% RH to initiate wound periderm beneath the sclerified parenchyma cells within 48 hours (William *et al.*, 1990). In the current study, the storage condition for strawberry (10±1^{o}C and 70±5% RH) was higher than a recommended temperature for strawberry storage at 0^{o}C with 90-95% RH (Mitcham, 2014). A range of temperatures in the supply chain of strawberries was at approximately 3-17^{o}C (Russell *et al.*, 2009; Nunes *et al.*, 2009; Chaiwong and Bishop, 2015). Thus, it is possible that a cool temperature at 10^{o}C during storage may be a possible optimum temperature for wound healing of dry bruise in strawberries for 3 days.

Nevertheless, the changes of EC value in ‘Elsanta’ and ‘Sonata’ strawberries differed from those of bruised pears. The EC value of pears increased as fruit softened during storage at 23^{o}C and after an actual transport (Zhou *et al.*, 2007). The EC values of ‘Fuerte’ avocado and ‘Kyoho’ table grape also increased during storage, which is related to a reduction of firmness or fruit texture (Ahamed *et al.*, 2010; Deng *et al.*, 2005). Therefore, the changes of EC value in non-climateric or climacteric fruits during storage may relate to either fruit bruise or fruit ripening.

In this vibration study, EC showed a stronger correlation with wet bruise and severity score than both firmness measurements (Table 5.8). Interestingly, EC had a greater accuracy with wet bruise damage in both cultivars than the fruit firmness tests with a significantly higher correlation coefficient value (r = 0.482 to 0.928), with a particularly strong correlation of the summer cultivation (Tables 5.7 and 5.8). These findings are in agreement with the wet bruise detection by the EC method with significant and consistent correlations from the impact test (Tables 4.8 and 4.9). From the results of the vibration and impact tests, therefore, the EC technique is greatly recommended to apply the bruise evaluation of an individual strawberry for the rapid technique of non-destructive method. Also, it would be interesting to assess the bruise evaluation of a whole strawberry punnet and other soft fruits in postharvest handling and transport. Moreover, EC values on day 0 (initial day) showed a significantly strong relationship and a consistent result with bruise damages from both impact and vibration tests on day 3 (after storage for 3 days) (Tables 4.7 and 5.8). A strong linear correlation between EC value and bruise damage is suggested as a bruise predictor and could be developed for mathematical modelling to estimate bruise in strawberries and soft fruits or even a rapid damage assessment method of still packed fruit.

5.6.3 Fruit firmness and fruit weight

There was a wide range of fruit size in the summer cultivation due to constrained yield production, particularly for large fruit in control samples of 'Sonata' cultivar. The result showed that the fruit weight had a significant relationship with fruit firmness by compression (r = 0.770) and puncture (r = 0.545) tests (Tables 5.8). In 'Sonata' cultivar from the summer cultivation, compression value in control samples was higher than the vibrated fruits, which correlated to a bigger fruit of control treatment (Table 5.4 and 5.5). However, the control treatment of 'Elsanta' fruits (summer) did not show a significant difference of fruit firmness even if there was a bigger fruit (Table 5.1). Hence, the fruit size by weight may relate to fruit firmness and strawberry cultivar.

At lower frequency and less exposure time, there was not a significant difference in fruit firmness by both puncture and compression tests, especially for 'Elsanta' cultivar (Tables 5.1- 5.2 and 5.4-5.5). After storage for 3 days, control treatment had firmer fruit by compression test than the vibrated fruits (Tables 5.2 and 5.5). Døving and Måge (2002) reported that the relationship between fruit size and firmness of strawberries is not consistent and depends on the method testing and cultivar. In the current study, to determine the type of strawberry bruise, the puncture test also gave a higher correlation with wet bruise than the compression test (Table 5.8), which were agreed with the correlation results of the impact test (Tables 4.5 and 4.6). The puncture test has most often been used to determine strawberry firmness. In a study of the simulated vibration at 9 Hz from 6 to 8 hours, the vibrated strawberries showed a reduction of firmness from 13.4% to 22% as compared to that of firm fruit before testing (Scalia *et al.*, 2015). Tatara *et al.* (1999) found that the vibration of strawberries affected a reduction of firmness by puncture test. Alayunt *et al.* (1998) reported that the frequencies (2.5 and 7.5 Hz) and exposure times (600 and 1200 sec) for vibration test in fig fruits significantly changed a reduction of firmness and an increase of weight loss. Converse study was reported by Fischer *et al*. (1992), in which it was shown that there was no effect on firmness and maximum damage fruits when vibration condition was a frequency of 5 to 10 Hz (0.6 *g*) for 600 sec.

In the current study, the firmness by puncture test can be confirmed for the determination of vibrated fruits and impacted fruits. However, in the previous studies on fruit firmness, it was mentioned that was the inconsistent technique of firmness method. The variable techniques rely on the method of testing; probe size, instrument, fruit size and fruit temperature. Therefore, the efficient detection of bruised strawberries will be considered in variable techniques**.**

5.6.4 Respiration rate

At 10^{o}C, the respiration rate of strawberries (a non-climacteric fruit) was quoted, regardless of variety as typically 50-100 mgCO_2/kg.hr (Mitcham, 2014). In this vibration study, the overall respiration rate of undamaged fruits from both cultivars in winter season was 32-36 mgCO_2/kg.hr, which was a lower level than in the summer season (46-55 mgCO_2/kg.hr) (Figures 5.13-5.14 and 5.28-5.29). The maximum value from bruised fruits in impact test was approximately higher than that value of vibration test by approximately 10 mgCO_2/kg.hr (Figures 4.7 and 4.14). On the other hand, the respiration rates of fruit from vibration tests was poorly differentiated in bruising levels in the winter cultivation, which conversely differed from the results of the impact test in the summer cultivation where there were differences in respiration rate. There is a possibility that the evaluation of respiration rate depended on fruit severity and is limited to detect the cases of either the lowest bruise or the highest bruise. These results with strawberries and respiration rate are different to cranberries where the respiration rate could be used as an indicator of mechanical damage in cranberries (Massey *et al.*, 1982). In the current strawberry study, the overall highest respiration rate of both cultivars occurred at the vibration level at 5 Hz, followed by 4, 3 Hz and control (Figures 5.14 and 5.29), which related to bruise level and severity score (Figures 5.16 and 5.31). Therefore, the method of respiration rate was limited to the detection of bruised strawberries with various severities, especially either the lowest or highest severity.

The vibration level affected an increase of respiration rate due to an increasing frequency and the exposure time. The highest respiration rate was often found in a frequency of 5 Hz in each exposure time, which was higher than a control punnet by 14-21% (winter) and 14-26% (summer) at the initial hour. In literature, the respiration rate of bruised strawberries from vibration test increased by 40% at 5°C and 17% at 15°C when compared with undamaged fruits (Tatara *et al*., 1999). Lui and Kojima (1997) reported that strawberries vibrated from acceleration at 0.5 *g* for 3600 sec caused an increase of respiration rate and related to a rise of temperature storage from 0 to 20°C. However, Fischer *et al.* (1992) reported the respiration rate of strawberries after the vibration treatment had an unclear pattern. In this vibration study, the pattern of respiration rate in strawberries showed the maximum level at the initial hour and then gradually reduced throughout the entire storage after vibration test, including control samples (Figures 5.13-5.14 and 5.28-5.29). These pattern changes match the respiration rate of unbruised or bruised 'Manzanilla' olives (a non-climacteric fruit) at 25°C (Segovia-Bravo *et al*., 2011). In climacteric fruits, respiration rate of either bruised 'Fuji' apples or fig fruits increased after vibration test, with particularly high CO_2 production in vibrated fruits (Jung and Park, 2012; Mao *et al*., 1995). The vibration level affected notably an increase of respiration rate, whereas the changing pattern of CO_2 production after vibration and storage may depend on the type of climacteric or non-climacteric fruits.

5.6.5 TSS, TA and TSS:TA contents, colour, and weight loss (%)

The vibration level with different frequencies and exposure times did not affect the overall results of TSS, TA and TSS:TA contents in ‘Elsanata’ and ‘Sonata’ after vibration test ($p>0.05$) (Figures 5.6, 5.8, 5.21 and 5.23). Tatara *et al.* (1999) found that the vibration test on strawberries had no effect on TSS and TA contents. However, Lui and Kojima (1997) reported that a reduction of TSS content caused the vibration of strawberries when the storage temperature from was increased from 0 to 20°C for 3 days. Nakamura *et al.* (1986) reported that vibrated tomato and Japanese pear fruits at acceleration 3 *g* for 18000 sec showed a rapid reduction in citric and malic acids when compared with 1 *g*. In this vibration study, the low temperature storage did not affect TSS, TA and TSS:TA contents of any vibrated fruits (Figures 5.7, 5.9, 5.22 and 5.24). Also, these findings agreed with all these contents in the impact test from a height of 0 to 1000 mm (Figures 4.4-4.5 and 4.11-4.12). According to the results of this research, the bruised strawberries from both the vibration and impact tests did not cause changes of TSS, TA and TSS:TA levels. Thus, the strawberry damage in various severity could not affect sugar and acid contents.

As regards colour changes, lightness (L*) and chroma (C*) values of vibrated fruits did not significantly differ in all frequencies and exposure times, including control samples ($p>0.05$). In both cultivars, control samples showed a significantly higher hue angle (h*) than those fruits vibrated for the exposure time of 100 and 150 sec (a deep red) (Figure 5.11-5.12 and 5.26-5.27). Samin and Banks (1993) reported that a reduction of h* value indicated apple browning. Zhou *et al.* (2007) found that control samples of pear also had a higher h* value than the vibrated pear fruits from the rear-top and front-top positions in a transport. In the pear study, the frequencies of peak in PD spectra at the front and rear positions during highway transport were 4 Hz and 3.5 Hz, respectively. Mechanical damage from transport vibration had an increase of colour changes when compared with intact fruit during storage at room temperature.

Recently, the colour of vibrated 'Florida Frotuna' strawberries was reported by Scalia *et al.* (2015). The vibration level at a frequency of 9 Hz showed a significant change in red (a*), yellow (b*), chroma (C*) and hue angle (h*) values ($p \leq 0.01$) after simulated vibration at $4^{o}C$ for 8 hours and refrigerated storage for 144 hours (6 days) when compared to initial quality. The h* value of treated strawberries started to decrease from the end of the simulated vibration for 8 hours when compared to the initial value. In the current study, the two results from vibration and impact tests of 'Elsanta' and 'Sonata' strawberries match those results observed in the above mentioned studies. The undamaged or less damaged fruits had a higher value of colour attributes than damaged fruits after testing and low temperature storage. Even some colour attributes could distinguish strawberry bruise from control fruits; however, the colour changes also was affected by the storage temperature and period of time as discussed in the section 4.6.2.4. Thus the colour measurement was also difficult to differentiate levels of bruise.

Bruising damage on the surface structure of harvested produce allows a greater evaporation (Will *et al*., 2007). Comparing the overall results of weight loss, there was not a significant weight loss between the intact fruits and the vibrated fruits throughout the storage (Figures 5.3 and 5.6). The weight loss (%) of strawberries was approximately 2-3%, which was the same level as bruised fruits from the impact test. Robinson *et al.* (1975) stated that the highest weight loss (6%) was considered for a limited sale of strawberries. In this vibration study, during storage at $10^{o}C$ for 3 days, the strawberry bruises from both tests may have little effect on the weight loss, while bruises may relate to colour changes due to a lower h* value (a deep red). Nunes and Emond (2007) reported that weight loss of strawberries has a strong correlation with colour changes from visual assessment (r = 0.940). There have been a number of strawberry colour studies during low storage temperature. The strawberry surface colour turns to a darker or deep red, which may relate to anthocyanin concentration (Sacks and Shaw, 1993; Hernanz *et al.*, 2008; Holcroft and Kader, 1999). Thus, changes of surface colour in strawberry bruise may involve the effect on low storage temperature and an increase of weight loss during storage.

5.7 CONCLUSION

The summer cultivation produced higher quantity and severity of bruise than the winter cultivation after the vibration test. The later harvesting with high temperature during growing in the summer increased vibrational bruise in ‘Sonata’ cultivar. ‘Sonata’ strawberries showed more bruise susceptibility than ‘Elsanta’ fruits, particularly at a high frequency of 5 Hz (1.1 *g*) for 100 and 150 sec in the summer cultivation. The vibrated fruits had the minimum severity score, fruit firmness and colour attributes as compared to control fruits. An increase in frequency and exposure time gave a gradual increase of wet bruise and EC value. The vibration level at a frequency of 5 Hz (1.1 *g*) for 150 sec was an important condition to reach the maximum wet bruise, EC value and respiration rate. Immediately after vibration test and cool storage, the vibrated fruits at the frequency of 5 Hz in both cultivars had an overall severity score over all 3 levels of acceptable score, except the vibrated ‘Sonata’ fruits at a frequency of 5 Hz for 100 and 150 sec. After storage at 10^{o}C for 3 days, a tendency of bruised strawberries was a gradual increase and a reduction of EC value. Nevertheless, the vibration condition did not affect TSS, TA, TSS:TA contents.

As mentioned in this chapter, the bruising level of either quality or severity on a visual assessment had a close significant correlation with the differences in EC value as compared to firmness and respiration rate measurements. The EC technique gave consistently a significant correlation result with wet bruise and severity score in different preharvest and postharvest factors such as cultivar, cultivation and period of storage. The EC technique is suggested to use as a bruise indicator from vibration damage as well as a bruise predictor. Further studies on the current results are therefore recommended to apply the EC method for the bruise determination of a full strawberry punnet and other soft fruits in terms of a rapid non-destructive method.

CHAPTER 6
MEASUREMENT AND ANALYSIS OF VIBRATION AND TEMPERATURE IN REFRIGERATED TRUCK AND SEMI-TRAILER DURING FOOD TRANSPORT ON THE LONDON AND MANCHESTER ROUTES

6.1 INTRODUCTION

Vehicle vibration during transport is commonly referred to as random vibration, which is exposure to vibration at multiple frequencies during travelling. The acceleration (*g*) character of vehicle vibration cannot repeat in the same pattern during the actual transport (Marcondes, 2009). In most cases, the truck vibration levels were analysed and computerized values in terms of power, acceleration (*g*), root mean square acceleration (g_{rms}), and power spectrum density (PSD) (Lu *et al.*, 2010a). Most published journals use PSD value (G^2/Hz), which indicate at which frequency a strong (high PSD) or a weak point (low PSD) is given in each travelling vehicle (Singh *et al.*, 2006). At a specific frequency, the power density (PD) frequency peak may indicate the quality of the road and/or vehicle (Marcondes, 2009). In the literature, the summarized frequency of the PSD peak could be classified into low and medium frequency ranges, these low and medium frequencies were considered to be 1-5 Hz and 10-16 Hz, respectively (Chonhenchob *et al.*, 2009; Barchi *et al.*, 2002; Berardinelli *et al.*, 2005). However, this study is reported in PD value as referred from the formula giving by Marcondes (2009) (section 2.5.1).

Regarding a coordinate system, a Cartesian coordinate commonly consists of X-axis (lateral vibration), Y-axis (longitudinal vibration) and Z-axis (vertical vibration). For the actual transport, the dominant coordinate of the highest vibration was often represented by vertical vibration (Z-axis) during monitoring vibration levels in truck, van and rail shipments (Chonhenchob *et al.*, 2009, 2010, 2012; Lu *et al.*, 2010a; Rissi *et al.*, 2008).

Over the past decade, there has been a dramatic increase in vibration studies of fresh produce during transport. The leading countries in this research are mainly in Asian countries, namely

Thailand (Chonhenchob *et al.*, 2010), Japan (Lu *et al.*, 2008), China (Zhou *et al.*, 2007), India (Singh *et al.*, 2007b) and Sri Lanka (Ranathunga *et al.*, 2010). Additionally, the various factors found to be influencing the vibration level during transport have been explored in several factor studies. The summarized factors commonly investigated are the position of the load in the vehicle and position of the pallet in the stack, including vehicle suspension, payload, truck size, truck speed and surface condition (Berardinelli *et al.*, 2005; Garcia-Romeu-Martinez *et al.*, 2008; Jarimopas *et al.*, 2005; Lu *et al.*, 2010a; Singh *et al.*, 2006). It is interesting to note that all studies have been done on full loads of a single product.

In the different positions of the load in the vehicle, the rear position gave a higher g_{rms} as compared to the middle or front position (Berardinelli *et al.*, 2005, Hinsch *et al.*, 1993, Soleimani and Ahmadi, 2014) as well as the highest value of peak PSD spectra at the rear position (Zhou *et al.*, 2007; Barchi *et al.*, 2002). The top package of a pallet showed a stronger vibration level (g_{rms}) than the middle or bottom package of a pallet (Barchi *et al.*, 2002; Berardinelli *et al.*, 2005; Hinsch *et al.*; 1993, Ranathunga *et al.*, 2010*;* Soleimani and Ahmadi, 2014; Slaughter *et al.*, 1993). Additionally, air-ride suspension can reduce vibration level when compared to the leaf spring type (Garcia-Romeu-Martinez *et al.*, 2008; Hinsch *et al.*, 1993; Singh *et al.*, 2006; Timm *et al.*, 1996; Soleimani and Ahmadi, 2014; Zeebroeck *et al.*, 2008). Therefore, the strongest vibration level may occur in the top-rear position with a leaf spring suspension; however, the vibration level varied with truck speed and surface condition for each route travelled.

In the UK shipment, the trucks and semi-trailers for goods shipment are classified into 15 types, with two basic kinds of description: the number of axles (2 to 6 axles) and maximum gross weight (over 3.5 to 44 tonnes) (Department of Transport, 2003). In the case of temperature controlled food transport, the air circulation system must be concerned with removing vital heat from the product (Ashby, 2008), and a top-air delivery or overhead system is commonly used in refrigerated semi-trailers (Vigneault *et al.*, 2009). A uniform air distribution was often found in the area from front to rear position and along the stack (Hui *et al.*, 2006; Harvey *et al.*, 1980; Rediers *et al.*, 2009; Pelletier *et al.*, 2011).

Until recently, there has been no previous research into vibration during food transport and distribution in the UK. In addition, little published research has been found that surveyed vibration levels and temperature profiles during transport in mixed loads of food products, particularly in the food service industry. However, most studies in the fields of packaging or engineering have focussed on the shipment of a single product with a full load throughout the entire transport (a single drop). No research has been found that surveyed the different aspects from previous studies, for example, mixed loads with different products in each package, different packages (size, type) in each pallet, and different stack and load in each shipment. Moreover, a multi drop delivery was scenario and also monitored to show the changes of vibration level on the London route. Questions have been raised about the effect of the different mixed load conditions and multi drop deliveries on the vibration levels.

Several attempts have been investigated to the position of the load or of the stack. Very little is known about the vibration level in the comparison between right and left positions or with the multi drop deliveries. The four hypotheses that will be tested are

a) The refrigerated vehicle and travelling route will give a difference to the vibration and temperature levels.
b) The location on the refrigerated delivery vehicle will make a difference to the vibration and temperature levels.
c) The multidrop deliveries with partially loaded vehicles will give higher vibration levels for the same location than the fully loaded single drop delivery
d) The temperature will remain uniform (± 1^{o}C) during shipment in refrigerated vehicles in city and on the long distance deliveries.

As explained in the above-mentioned studies and the lack of research in these fields in the UK, this chapter describes and discusses the methodology, results and discussion from the actual transport of mixed loads on the London and Manchester routes, which started from Reynolds Catering Supplies Ltd in London. The shipments on the London routes varied in the percentage of loading with the multi drop deliveries, whereas the single drop was investigated on the

Manchester route. Furthermore, this study was carried out with the kind co-operation of the Reynolds company in London.

6.2 MATERIALS AND METHODS

The transport research is a survey study to monitor vibration and temperature levels was mainly supported by Reynolds Catering Supplies Ltd, which has been one of the leading companies for fresh produce suppliers to the UK food service industry. Reynolds company supplies a wide range of food products such as fruits and vegetables, as well as dairy products, cheese and alcoholic drinks to the food services sector. All food shipments in this study were a mixed load that meant the various food products or a single product in each package. The different packages were corrugated fibreboard box, common footprint tray and plastic crate with disuniform pattern for stacking on pallets. Therefore, the pallet load in each shipment depended on client requirement. Also, the limitation of this study was a number of vibration loggers (a logger in each location; therefore the result could not show a significant difference from the data analysis. The methodological procedure taken in this study was to collect and record information based on vehicles, routes, vibration and temperature during food delivery.

6.2.1 Vehicles and routes

The period of the transport study was carried out from May to August in 2014. The vehicles used for the food transport of three sizes. There were refrigerated trucks (18 and 26 tonnes) and a semi-trailer (44 tonnes). Three routes for the food delivery were monitored on two major routes, namely the London routes (WC 100 and 109) and the Manchester route. In order to measure and record the characteristics of vehicle and route, the following equipment was used.

6.2.1.1 Vehicles

For this study, two types of refrigerated trucks were used: 18 and 26 tonnes on the London route (Figure 6.1-6.2). The semi-trailer was used 44 tonnes on the Manchester route (Figure 6.3). The tyre inflation pressure of both vehicles was regularly checked to be 105 psi. The main information about the vehicle characteristics was received from Reynolds Catering Supplies Ltd and the following information was recorded for each shipment:

a) License plate
b) Date of manufacturing (year)
c) Permissible maximum weight (tonne)
d) Payload (tonne)
e) Total loaded pallet (%)
f) Number of axles
g) Suspension type

Figure 6.1: A refrigerated truck of 18 tonnes on the London route. *Source*: Chaiwong (2015).

Figure 6.2: A refrigerated truck of 26 tonnes on the London route. *Source*: Chaiwong (2015).

Figure 6.3: A semi-trailer (44 tonnes) on the Manchester route. *Source*: Chaiwong (2015).

6.2.1.2 Routes

The three food delivery routes were selected, namely, WC100 (the east of London), WC109 (the west of London) and Manchester. The three main considerations for the selected route in this study were daily food delivery, a similar delivery point and the same driver. A total of twelve shipments was investigated for the three routes leaving directly from Reynolds Catering Supplies Ltd, Watham Cross, London. The departure time for food delivery on the London route generally started at around 4:00 to 6:00 am and on the Manchester route at around 9:00 pm.

Table 6.1 shows the total of twelve shipments that were studied for the WC109 route (six shipments), the WC100 route (three shipments) and the Manchester route (three shipments). The global positioning satellite (GPS) tracking (Garmin Nuvi 50, Hamphire, UK) monitored the actual delivery locations (Figure 6.4). Shipment information was collected as follows:

a) Arrival place
b) Total travelling distance (km)
c) Total travelling time (min)
d) Average travelling speed (km/hr)

Figure 6.4: GPS (Garmin Nuvi 50). *Source*: Chaiwong (2015).

Table 6.1: Twelve shipments of the three routes in London and Manchester.

Shipment	Route	Refrigerated truck/ Semi-trailer (tonnes)	Date
1	WC100	18	22/7/2014
2	WC100	18	25/7/2014
3	WC100	18	29/8/2014
4	WC109	26	28/5/2014
5	WC109	18	20/6/2014
6	WC109	18	4/7/2014
7	WC109	18	7/7/2017
8	WC109	18	11/7/2014
9	WC109	18	14/7/2014
10	Manchester	44	18/7/2014
11	Manchester	44	28/7/2014
12	Manchester	44	1/8/2014

6.2.2 Loading configuration of trucks and semi-trailer

Loading layouts of the two refrigerated trucks had a maximum load of 14 pallets (18 tonnes) and of 16 pallets (26 tonnes) on the London route. The maximum load of semi-trailer was 40 pallets on the Manchester route. The loading configuration of all shipments was in two rows (Figures 6.5 and 6.7). The size of timber pallet used was 1,200 x 1,000 x 162 mm for food distribution (Euro pallet: EURO 1). Figures 6.5 and 6.6 show the top view pallet layout and loading performance of the refrigerated truck (18 and 26 tonnes) on the London route. In these investigations of loaded pallets on the London route, the number of loaded pallets was 7 to 14 pallets (over 50% of total loading).

In the Manchester shipment, the top view pallet layout is shown in Figure 6.7 and an actual load of food products in the semi-trailer (44 tonnes) is shown in Figure 6.8. The pallet layout of the semi-trailer (44 tonnes) can be divided into 3 sections for the maximum pallets load: front (F) (8 pallets), lower deck (LD) (16 pallets) and upper deck (UD) (16 pallets). All Manchester shipments were with a full load of 40 pallets. In addition, the patterns of loading layout in both semi-trailers were numbered to show the particular position for an attached vibration logger (Table 6.2).

(A)

1	**2**
3	**4**
5	**6**
7	**8**
9	**10**
11	**12**
13	**14**

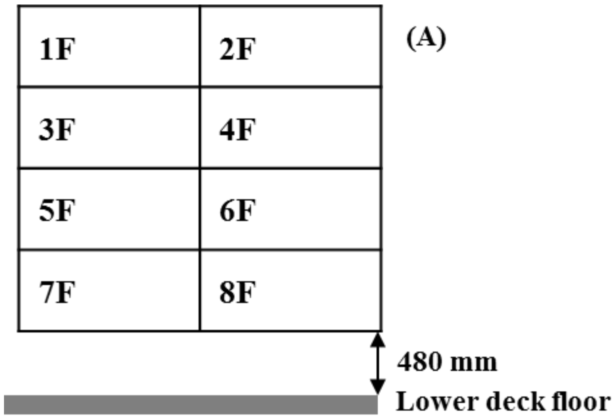
(B)

1	**2**
3	**4**
5	**6**
7	**8**
9	**10**
11	**12**
13	**14**
15	**16**

Figure 6.5: Top view pallet layout of the refrigerated truck on the London route (WC100 and WC109) 14 pallets of 18 tonnes (A) and (WC109) 16 pallets of 26 tonnes (B).

Figure 6.6: Loading configuration in the refrigerated truck (18 tonnes) on the London route. *Source*: Chaiwong (2015).

Front (F) section of loading layout on the Manchester route.



Lower deck (LD) (B) and upper deck (UD) (C) sections of loading layout on the Manchester route

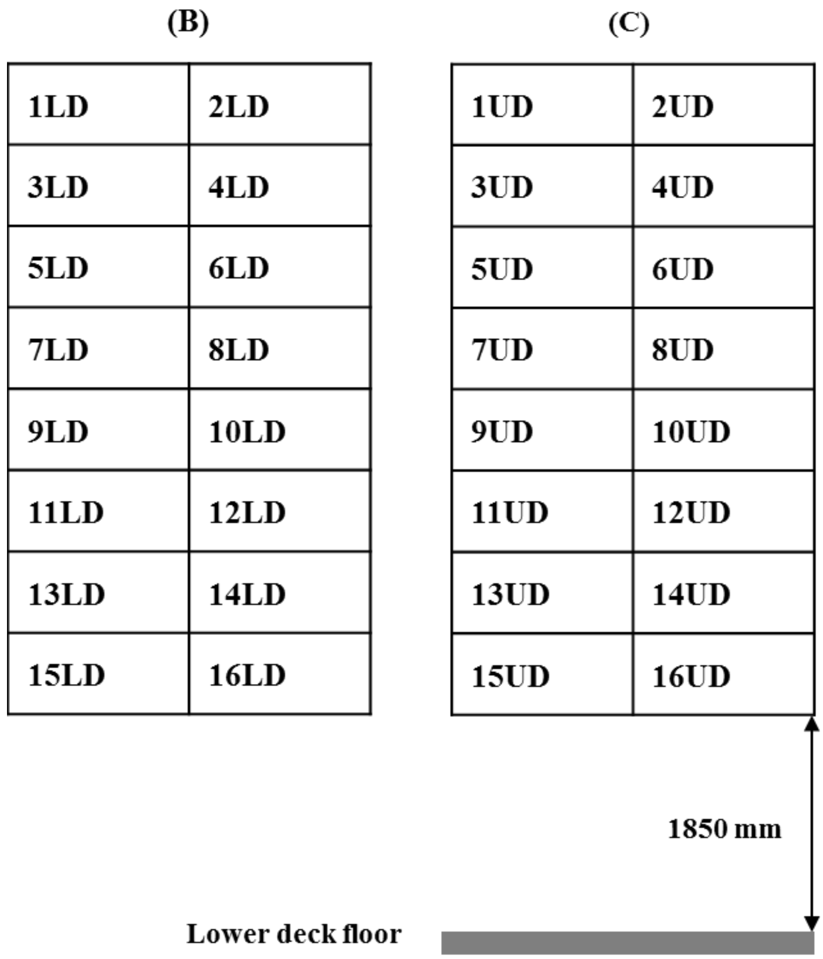


Figure 6.7: Top view pallet layout of the semi-trailer on the Manchester route in front section (A), lower deck (B), upper deck (C) (40 pallets).

Figure 6.8: Front (A), upper deck (B), and lower deck (C) sections of the semi-trailer (44 tonnes) on the Manchester route. *Source:* Chaiwong (2015).

6.2.3 Installation of vibration logger

In this study, vibration loggers were attached to the containers in all shipments in a vertical direction in all cases. The three vibration loggers were firmly attached to a corrugated fibreboard box or the plastic crate in different positions in the truck or semi-trailer (Figure 6.9). The height level (mm) of the attached logger on a food container was also measured from the floor of the refrigerated truck or semi-trailer. However, the height of the attached logger was kept at around 800 to 1500 mm in the case of the top position on the pallet, except in case C (top and bottom levels on the same pallet).

(A)

(B)

Figure 6.9: The attached vibration logger on the corrugated fibreboard box (A) or plastic crate (B). *Source*: Chaiwong (2015).

The four cases from three routes depended on the position of the attached vibration logger on the pallet:

i) Case A: Front, middle and rear positions of the top level along the length of the vehicle (8 trials)

ii) Case B: Left and right sides of the top level across the width of the vehicle (8 trials)

iii) Case C: Top and bottom levels on the same pallet (2 trials)

iv) Case D: Lower and upper decks of the top level in the middle position along the length of the vehicle (1 trial)

The total number of trials from four cases was 19 trials, namely case A (8 trials), case B (8 trials), case C (2 trials) and case D (1 trial). Case A (front, middle and rear positions) and case B (left and right sides) had the highest number of studies for 8 trials. Time constraints meant that only one trial of case D (lower and upper decks) on the Manchester route was possible. All load that were investigated as four cases are shown in Table 6.2.

Table 6.2: Pallet position of the vibration and temperature loggers in the refrigerated truck (shipment 1 to 9) and semi-trailer (shipment 10 to 12) from twelve shipments.

Shipment	Route	Date	Case	Pallet position	Travelling location
1	WC100	22/7/2014	A	5, 9	L0 to L3
			B	5, 6	L0 toL5
2	WC100	25/7/2014	A	1, 5	L0 to L5
			B	5,6	L0 to L5
3	WC100	29/8/2014	A	1, 5, 11	L0 to L2
4	WC109	28/5/2014	A	1, 5, 7	L0 to L2
5	WC109	20/6/2014	B	1, 2	L3 to L5
6	WC109	4/7/2014	A	1, 10	L0 to L1
7	WC109	7/7/2017	A	1, 5, 7	L0 to L1
			B	1, 2	L1 to L3
8	WC109	11/7/2014	B	5, 6	L0 to L4
			C	5	L0 to L4
9	WC109	14/7/2014	B	3, 4	L0 to L3
			C	3	L0 to L3
10	Manchester	18/7/2014	A	F5, LD7, LD15	L0 to L1
11	Manchester	28/7/2014	B	LD7, LD8	L0 to L1
			D	LD7, UD7	L0 to L1
12	Manchester	1/8/2014	A	UD7, UD15	L0 to L1
			B	UD7, UD8	L0 to L1

LD and UD mean lower deck and upper deck, respectively. F means front. L means a location of an unloading pallet as given information in Appendix 1.1-1.10, except L0 (a location of loading pallets).

6.2.4 Vibration measurement

The level of vibrations in the vehicles during transport was recorded by vibration logger model *SVR101* (MedgeTech, New Hampshire, USA) (Figure 6.10A).The vibration logger SVR101 is equipped with a tri-axial logger; therefore it is capable of recording vibration levels in all three directions.

6.2.4.1 Configuration of the vibration data loggers

The configuration of the data logger can be achieved via *Meadge Tech v 2.07.1* software. The same software is also used for downloading the logged data from the data loggers to compute for further post processing and analysis. In the experiment, the SVR101 was configured to sample vibration level at a sampling rate of 6 samples per minute in the range of acceleration between 1.0 to 50.0 *g* with a resolution of 0.05 *g*. It should be noted that the recorded vibration level indicates the *peak level* in the sample period. The spectrums of the vibration in the frequency range between 0 to 128 Hz with the frequency resolution of 1 Hz also computed in real-time.

The orientation of the data logger in the installation is crucial because there are now two Cartesian coordinates, that is, one coordinate corresponding to the vibration logger and one coordinate corresponding to the vehicle. When the logger is installed in the vehicle, then the former is regarded as the *logger coordinate* and the latter is regarded as the *vehicle coordinate*. Since the vibration logger has its own coordinate system, this means that the orientation of the logger must be considered as the adjustment of installation.

The coordinate system of the logger is referred to as (x, y, z). The coordinate system of the vibration levels of the vehicle is referred to as (X, Y, Z). The directions of the (x, y, z) and (X, Y, Z) coordinates are given according to the *right hand rule* convention. The relation between the reference axes of the logger and its orientation can be found in Figure 6.10A. Furthermore, according to the Cartesian coordinate system (X, Y, Z), the vibration levels are given as follows:

i) The lateral vibration (X-axis) denoted by a_X is the vibration levels measured along the back-and-front direction of the driver.

ii) The longitudinal vibration (Y-axis) denoted by a_Y is the vibration levels measured along the right-and-left direction of the driver.

iii) The vertical vibration (Z-axis) denoted by a_Z is the vibration levels measured along the up-and-down direction of the driver.

It should be noted that the vibration levels in the analysis are *total vibration levels* denoted by a_t that can be obtained by the following expression as shown in the formula (1).

$$a_t = \sqrt{a_X^2 + a_Y^2 + a_Z^2} \qquad (1)$$

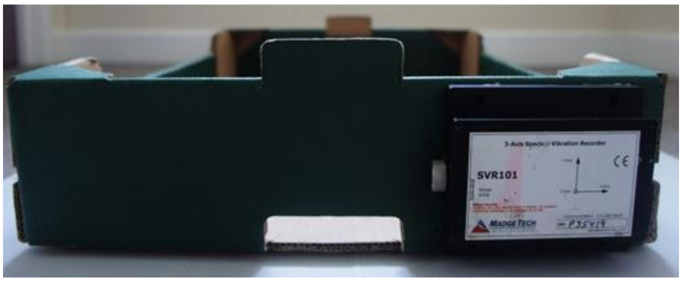
However, for the logger coordinates to perfectly match the vehicle coordinate is not feasible in practice due to some constraints such as full packing inside a corrugated common footprint or a plastic crate and a short loading time. Therefore, the loggers in all shipments were attached to the container in a vertical direction (not lying flat) as shown in Figure 6.10B. This implies that the two coordinates must be mapped as given in Table 6.3.

Furthermore, the data logger always measures 1 *g* of Z acceleration value (the vertical direction of vehicle coordinate) due to the gravity of the earth. Therefore, with the value of a Z-coordinate ('1.0') must be subtracted from the measured vibration level. Then the subtracted value was analysed for the total vibration level as shown in the formula (1).

Table 6.3: The vehicle and logger coordinates.

Vehicle coordinates	**Logger coordinates**	**Movement direction (positive - negative)**	**Direction reading**
X	x	Back - front	Lateral
Y	-z	Right - left	Longitudinal
Z	y	Up - down	Vertical

(A)



(B)

Figure 6.10: Vibration logger SVR101 (A) and the method of logger attachment onto the corrugated fibreboard box during measurement (B). *Source*: Chaiwong (2015).

6.2.5 Temperature measurement

The temperature in the refrigerated truck and semi-trailer was set at 3^{o}C for food shipments from Reynolds. A temperature logger with internal thermistor probe (Tinytag Talk2, Gemini Data Loggers Ltd., UK) was used to monitor temperature at the same location as each vibration logger. The sampling temperature was set to 2 seconds for recording (Figure 6.11).

Figure 6.11: Temperature logger (Tinytag Talk2). *Source*: Chaiwong (2015).

6.3 DATA ANALYSIS

The route results obtained from delivery tracking were analysed using *Garmin BaseCamp* software. The software shows the route and map of shipment and also reports total travelling distance (km), total travelling time (min), and average travelling speed (km/hr) from departure place to arrival place.

The vibration levels are presented by acceleration (g), root mean square acceleration (g_{rms}^{peak}) And power density (PD). It is mentioned in section 6.2.4.1 that the vibration loggers detect the maximum vibration level in a given period of time. The acceleration (g) is analysed and presented to acceleration distribution (%). There are the six ranges of acceleration distribution, namely 0.00-0.25 g, 0.26-0.50 g, 0.51-0.75 g, 0.76-1.00 g, 1.00-1.50 g and >1.50 g. The classification of g value is adapted from Vursavuş and Özgüven's report (2004).

The g_{rms}^{peak} level defined here is the *rms* level of the peak values over the route of interest given by the formula (2).

$$g_{rms}^{peak} = \sqrt{\frac{\sum_{n=1}^{N}\left(g_n^{peak}\right)^2}{N}} \qquad (2)$$

Where g_{rms}^{peak} indicates the *rms* value of the vibration level during travel, g_n^{peak} indicates the n-th of the vibration value provided by the vibration logger, N denotes the number of the total peak values. Notice that the superscript *peak* of g_{rms}^{peak} and g_n^{peak} emphasize that the vibration values involved in the calculation are peak values rather than raw data.

Vibration of vehicle produced by road surface is usually considered as a random vibration (Marchondes, 2009). Power density (PD) is a mathematical tool that is commonly used for random vibration analysis. By assuming that the vibration of a journey of interest is recorded, such data is then chopped into N set of data $G_{rms,n}$ where $n = 1, 2, \ldots, N$, the PD of the recorded vibration is given by the following formula (3) and reported in unit (G^2/Hz).

$$PD(f) = \frac{1}{BW} \frac{\sum_{n=1}^{N} G_{rms,n}^{2}(f)}{N} \qquad (3)$$

where f denotes frequencies in Hz, $PD(f)$ denotes a power density as a function of the frequency, $G_{rms,n}(f)$ denotes n-th snap shot of the root mean square magnitude of Fourier spectrum of acceleration, and BW denotes the bandwidth of the logged vibration data, which is normalized to 1 Hz in this case.

For this study, the analysed data of PD values were from 5 to 25 Hz on the London route, although all readings were in the range of 5 to 20 Hz and from 5 to 25 Hz on the Manchester route. These ranges can produce serious levels of strawberry damage (Nakamura *et al.*, 2007; Kojima *et al.*, 1999; Fischer *et al.*, 1992). Finally, graphical presentation of the data was made using the OriginPro 2015 Student version (Origin Lab Corporation). For clarity, the graph of PD value is a log-log scale at the low frequency level.

6.4 RESULTS

6.4.1 Vehicle and route characteristics

The derived information characteristics for the refrigerated truck and semi-trailer from the Reynolds company used in this study are shown in Tables 6.4-6.5. There were three sizes of trucks, categorized by permissible maximum weight, namely 18 and 26 tonnes (3 axles) and a 44 tonne semi-trailer (6 axles). The vehicles on the London and Manchester routes were manufactured in 2011 (a truck) and 2012 (a semi-trailer). The truck (London route) and semi-trailer (Manchester route) consist of leaf spring suspension and air-ride suspension, respectively. The range of loaded food products on the London route was 2.2 to 3.9 tonnes (50 to 100% of loaded pallet), while the loaded products of the Manchester delivery were 24 tonnes with a full load (100% of loaded pallets).

Reynolds company is located in Waltham Cross (London), which was the starting place for the total of twelve food shipments (Figures 6.12-6.14). Table 6.6 reports the results of food shipments during transport on the London and Manchester routes from May to August in 2014. After data analysis of tracking shipments by BaseCamp software, the overall travelling distance and time for the WC100 (the east of London) and the WC109 (the west of London) routes was approximately 50 km and 75 min, respectively. For travelling distances over 45 km, the average speed on the WC100 route was nearly 35 km/hr, whereas the range of average speeds on the WC109 route was 27-44 km/hr. On the Manchester route, the travelling distance was nearly 320 km, with an average travelling speed of 70 km/hr. Additionally, the detail of twelve shipments will be explained in Appendices 1.1-1.10. The unloading place, travelling distance, time and average of speed are reported for each case and food shipment on the London and Manchester routes (Appendices 1.1-1.10).

Table 6.4: Permissible maximum weight of refrigerated trucks and semi-trailers on the London and Manchester routes.

Shipment	Route	Date	Vehicle licence plate	Date of manufacturing	Permissible maximum weight (tonne)
1	WC100	22/7/2014	CN60 CEY	2011	18
2	WC100	25/7/2014	HYII UEX	2011	18
3	WC100	29/8/2014	HYII UEW	2011	18
4	WC109	28/5/2014	CN60 CEV	2011	26
5	WC109	20/6/2014	HYII UEU	2011	18
6	WC109	4/7/2014	HYII UEW	2011	18
7	WC109	7/7/2017	HYII UEV	2011	18
8	WC109	11/7/2014	HYII UEV	2011	18
9	WC109	14/7/2014	HYII UEV	2011	18
10	Manchester	18/7/2014	WUI2 CJO	2012	44
11	Manchester	28/7/2014	WUI2 CJO	2012	44
12	Manchester	1/8/2014	WUI2 CJO	2012	44

Table 6.5: Loaded pallets, axles and suspension of refrigerated trucks and semi-trailers on the London and Manchester routes.

Shipment	Route	Loaded mass during trial (tonne)	% Loaded Pallet	No. of axles	Suspension
1	WC100	2.9	86	3	Leaf spring
2	WC100	3.1	100	3	Leaf spring
3	WC100	3.8	93	3	Leaf spring
4	WC109	2.2	50	3	Leaf spring
5	WC109	3.0	71	3	Leaf spring
6	WC109	3.5	79	3	Leaf spring
7	WC109	2.4	57	3	Leaf spring
8	WC109	3.9	86	3	Leaf spring
9	WC109	2.2	50	3	Leaf spring
10	Manchester	24.0	100	6	Air-ride
11	Manchester	24.0	100	6	Air-ride
12	Manchester	24.0	100	6	Air-ride

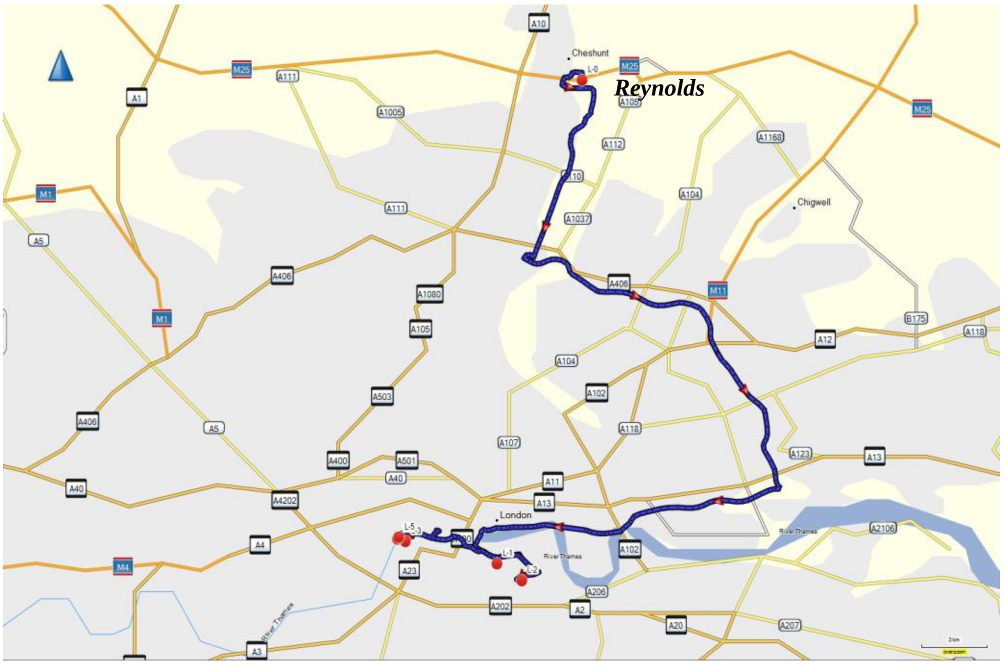


Figure 6.12: The WC100 route of London shipment (the east of London) during July to August in 2014. *Source*: Chaiwong (2015).

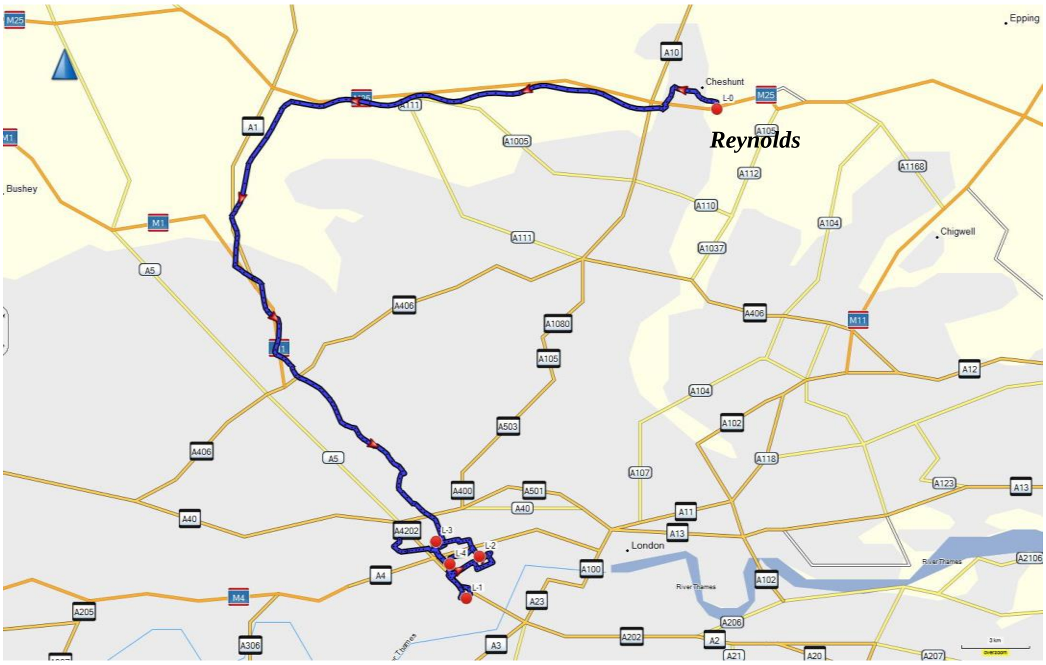


Figure 6.13: The WC109 route of London shipment (the west of London) during May to July in 2014. *Source*: Chaiwong (2015).

Figure 6.14: The Manchester shipment during July to August in 2014. *Source*: Chaiwong (2015).

Table 6.6: Main characteristics of information shipments on the London and Manchester routes from May to August in 2014.

Shipment	Route	Date	Case	Distance (km)	Travelling location	Duration (min)	Average speed (km/hr)
1	WC100	22/7/2014	A	47.934	L0 to L3	80	34.6
			B	1.624	L0 toL5	7	56.4
2	WC100	25/7/2014	A	49.131	L0 to L5	80	30.2
			B	49.131	L0 to L5	80	30.2
3	WC100	29/8/2014	A	43.242	L0 to L2	53	36.1
4	WC109	28/5/2014	A	45.246	L0 to L2	56	37.1
5	WC109	20/6/2014	B	5.623	L3 to L5	29	26.2
6	WC109	4/7/2014	A	42.341	L0 to L1	60	37.6
7	WC109	7/7/2017	A	45.266	L0 to L1	52	43.9
			B	1.881	L1 to L3	5	24.4
8	WC109	11/7/2014	B	48.286	L0 to L4	74	27.8
			C	48.286	L0 to L4	74	27.8
9	WC109	14/7/2014	B	47.538	L0 to L3	71	32.0
			C	47.538	L0 to L3	71	32.0
10	Manchester	18/7/2014	A	314.005	L0 to L1	224	75.3
11	Manchester	28/7/2014	B	317.421	L0 to L1	222	76.2
			D	317.421	L0 to L1	222	76.2
12	Manchester	1/8/2014	A	319.550	L0 to L1	273	67.6
			B	319.550	L0 to L1	273	67.6

6.4.2 Acceleration distribution (%) during transport on the WC100, WC109 and Manchester routes

The absolute acceleration value of all case studies (A, B, C and D) was analysed as the percentage of acceleration distribution (%) and categorized into the six levels of acceleration from 0.00 *g* to more than 1.50 *g*. The *g* values of vehicle coordinates were presented to four coordinates, namely X-axis (lateral vibration), Y-axis (longitudinal vibration), Z-axis (vertical vibration) and total vibration (T-axis).

6.4.2.1 Acceleration distribution (%) during transport in case A

According to the results of case A (front, middle and real positions at top level) for 8 trials, the highest percentage of total vibration (T-axis) was in the acceleration range of 0.26-0.50 *g* (Figures 6.15-6.16), excluding top rear position on the Manchester route (Figure 6.17). The evaluations of front, middle and rear position were particularly considered in the acceleration of total vibration (T-axis). In the food delivery on the WC100 route (shipment 1-3), the rear position had a higher percentage of more than 0.5 *g* compared to those for the middle or front positions (Figure 6.15). These results in the rear position were confirmed by the other shipments in different road conditions on the WC109 and Manchester routes. The highest acceleration value (T-axis) of more than 0.5 *g* was also found in the rear position of the shipments (4, 7, 10 and 12) (Figures 6.16 and 6.17). On the Manchester route, the rear position on upper and lower deck showed approximately 50% of the total acceleration distribution with a range of 0.51-0.75 *g* (Figure 6.17), which was a higher acceleration than those on the London routes (Figures 6.15 and 6.16).

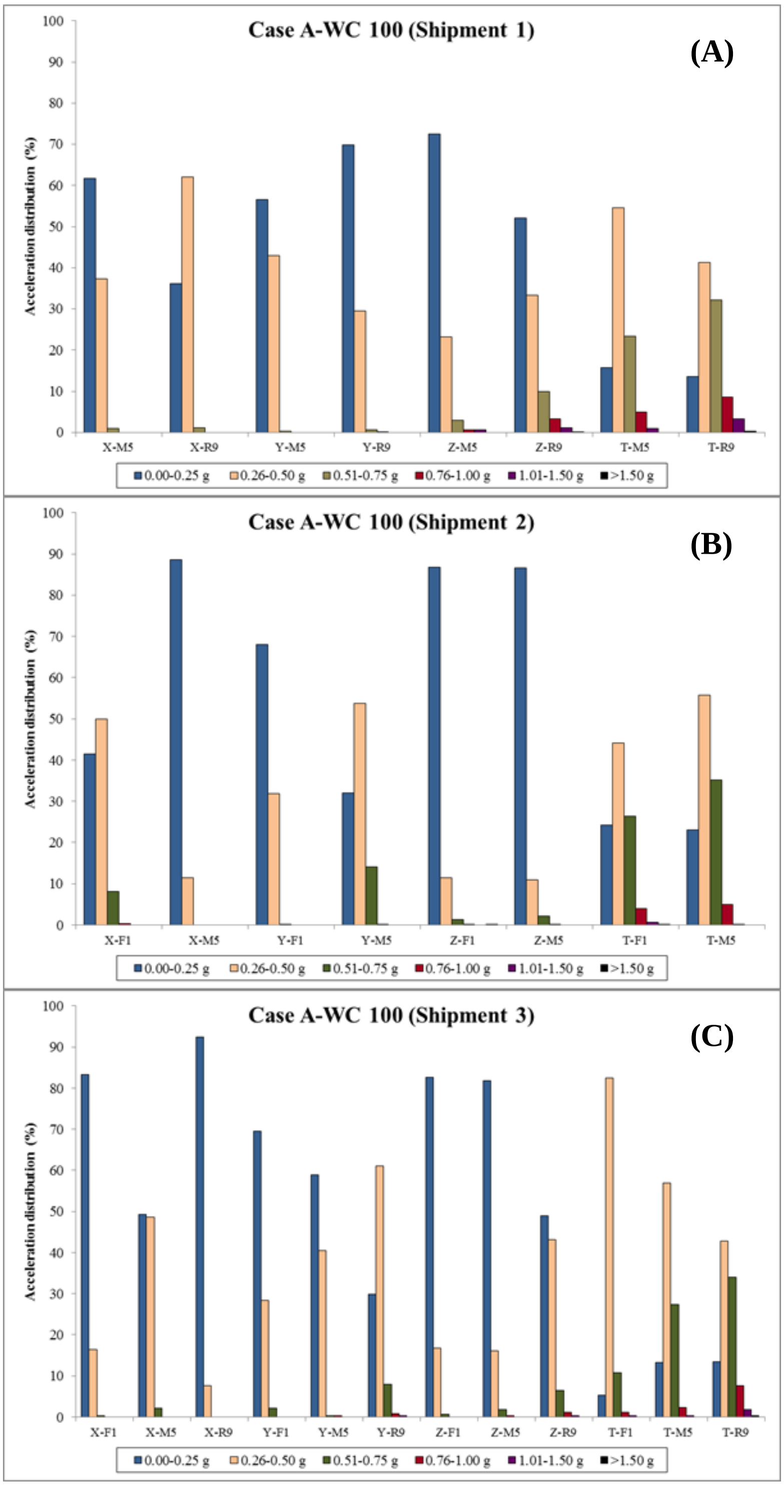


Figure 6.15: Acceleration distribution (%) of X, Y, Z and T vibrations in case A from shipment 1 (A), 2 (B) and 3 (C) on the WC100 route. The position was encoded as front (F), middle (M) and rear (R) with the pallet number.

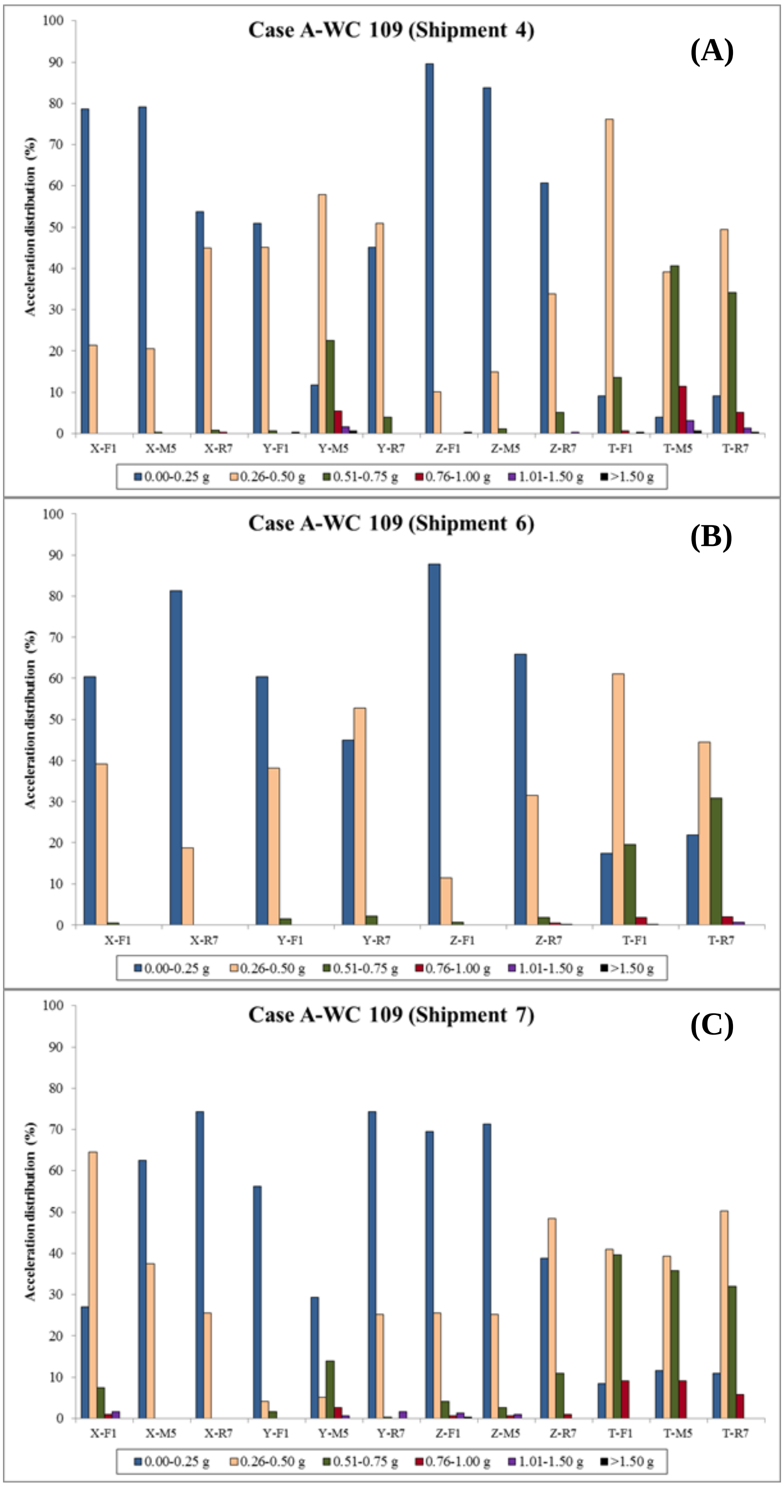


Figure 6.16: Acceleration distribution (%) of X, Y, Z and T vibrations in case A from shipment 4 (A), 6 (B) and 7 (C) on the WC109 route. The position was encoded as front (F), middle (M) and rear (R) with pallet number.

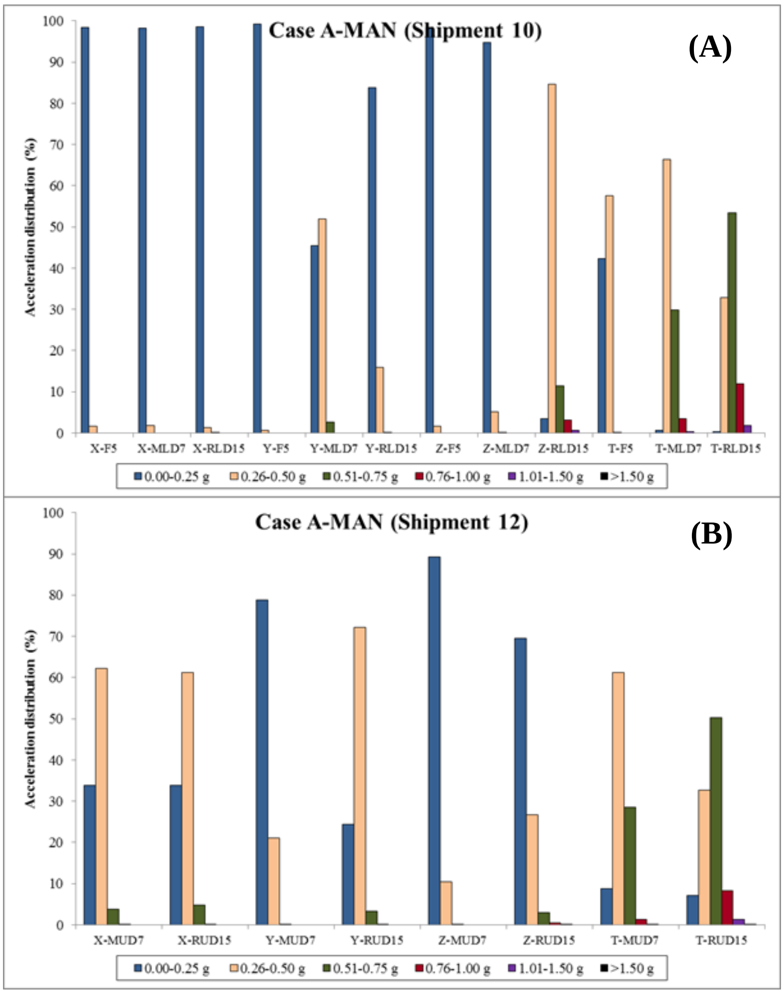


Figure 6.17: Acceleration distribution (%) of X, Y, Z and T vibrations in case A from shipment 10 (A) and 12 (B) on the Manchester route. The position was encoded as front (F), middle (M), rear (R), upper deck (UP) and lower deck (LD) with pallet number.

6.4.2.2 Acceleration distribution (%) during transport in case B, C and D

In case B (left and right positions at the top level) from 8 trials, the range of 0.26-0.50 *g* was still the highest percentage of the acceleration (T-axis) (>30%) on the WC100 route (Figure 6.18). The results of the WC109 and Manchester routes also were similar to the WC100 route (Figures 6.19 and 6.21). The acceleration of T-axis (>0.5 *g*) to the right pallet was almost the same level as the left pallet, which presented in shipment 1 (WC100), shipment 5 and 8 (WC109), and shipment 12 (Manchester) (Figures 6.8-6.10). However, the acceleration of T- axis more than 0.5 *g* varied on the transport routes. A high level of that acceleration was recorded at the right pallets (WC100: shipment 2 and Manchester: shipment 11) or at left pallets (WC109: shipment 7 and 9) (Figures 6.18 and 6.21).

The vibration level in case C (bottom-top level) was only investigated on the WC109 route. The result showed that the package at the top level gave a higher acceleration (>0.76 *g*) than at the bottom level (Figure 6.22B). The last case D (lower and upper deck) was carried out on the Manchester route and was only a short trial. The upper deck floor showed a greater acceleration than the lower deck floor, particularly for the ranges of acceleration at 0.51-0.75 *g* and 0.76-1.00 *g* (Figure 6.22C).

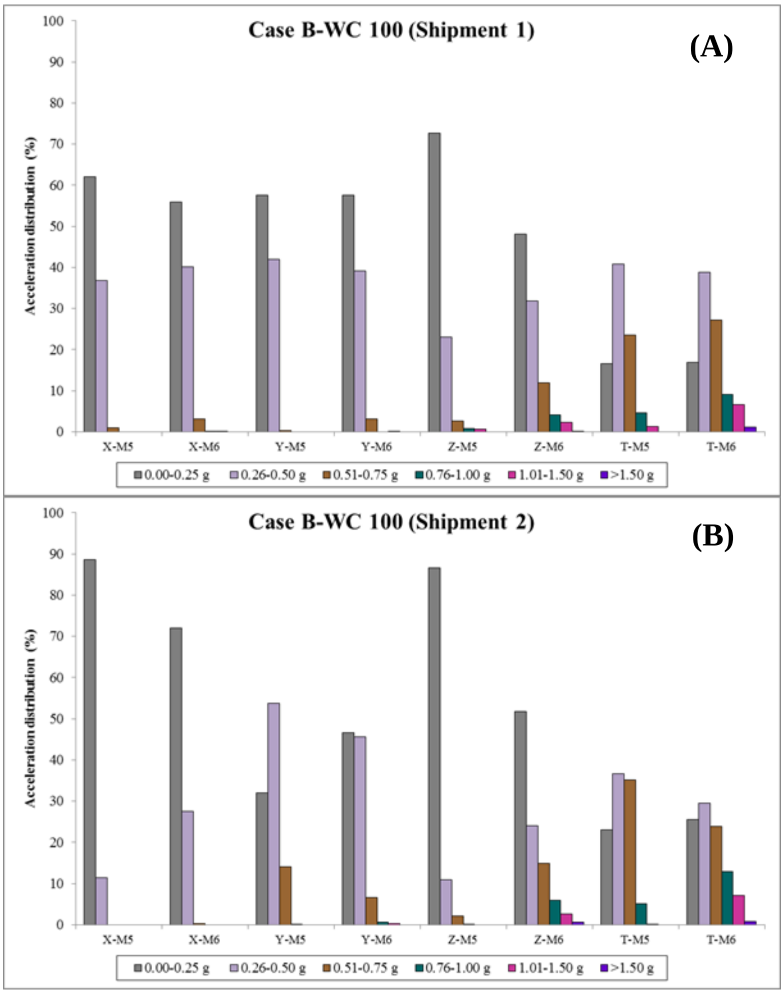


Figure 6.18: Acceleration distribution (%) of X, Y, Z and T vibrations in case B from shipment 1 (A) and 2 (B) on the WC100 route. The position was encoded as middle (M) with pallet number.

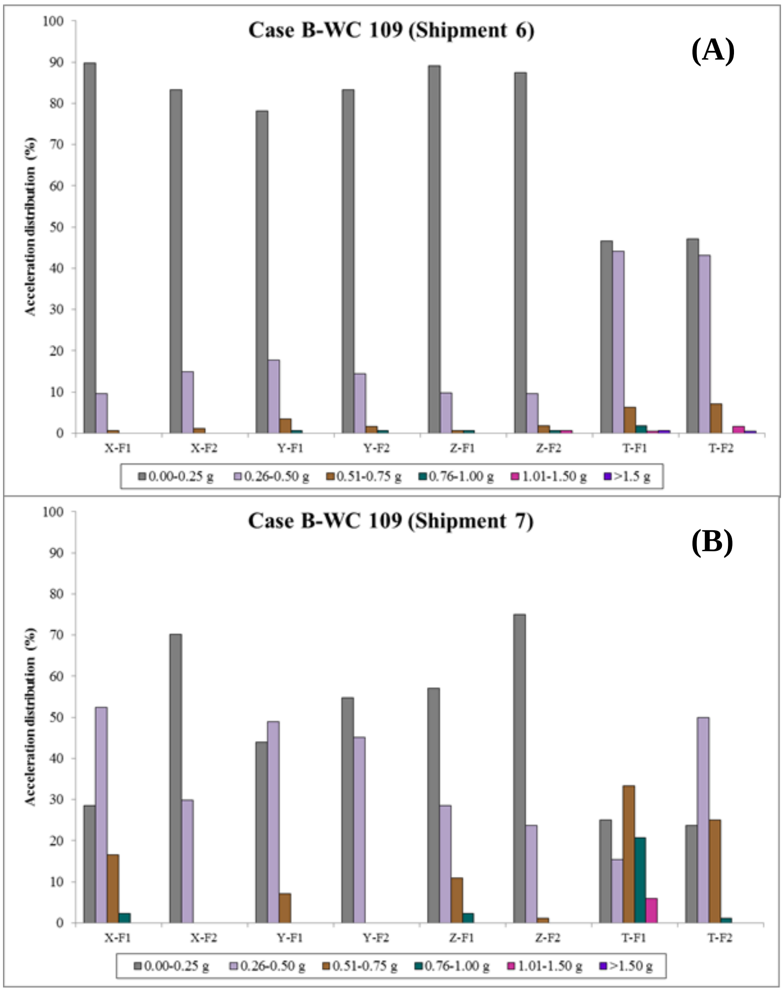


Figure 6.19: Acceleration distribution (%) of X, Y, Z and T vibrations in case B from shipment 6 (A) and 7 (B) on the WC100 route. The position was encoded as middle (M) with pallet number.

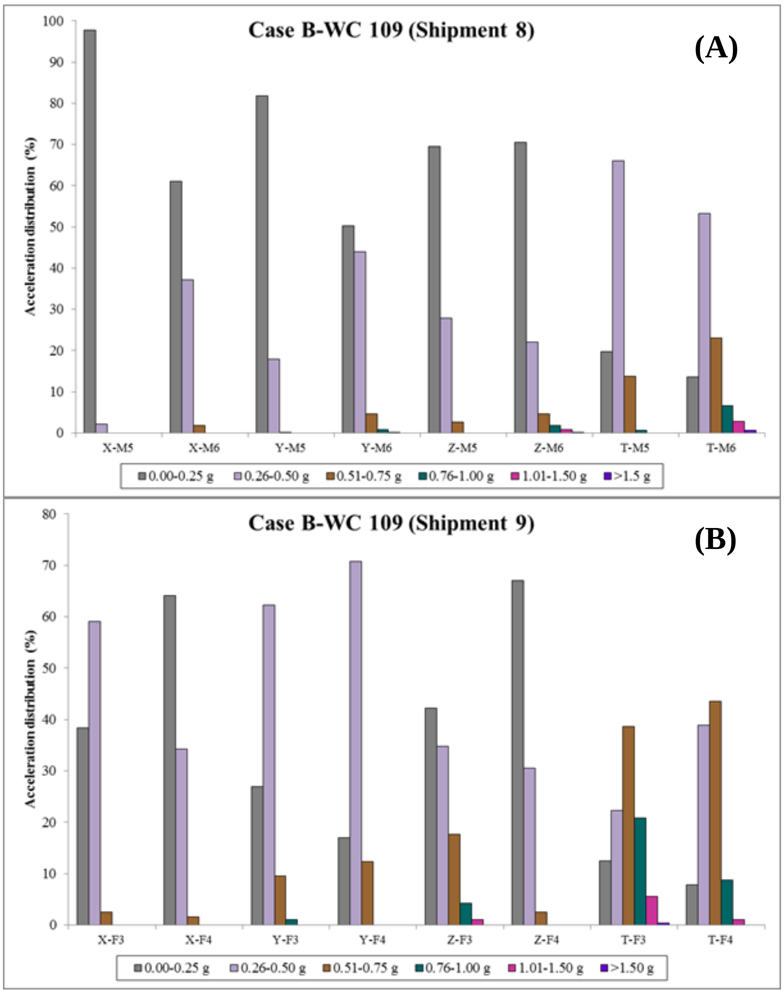


Figure 6.20: Acceleration distribution (%) of X, Y, Z and T vibrations in case B from shipment 8 (A) and 9 (B) on the WC100 route. The position was encoded as middle (M) with pallet number.

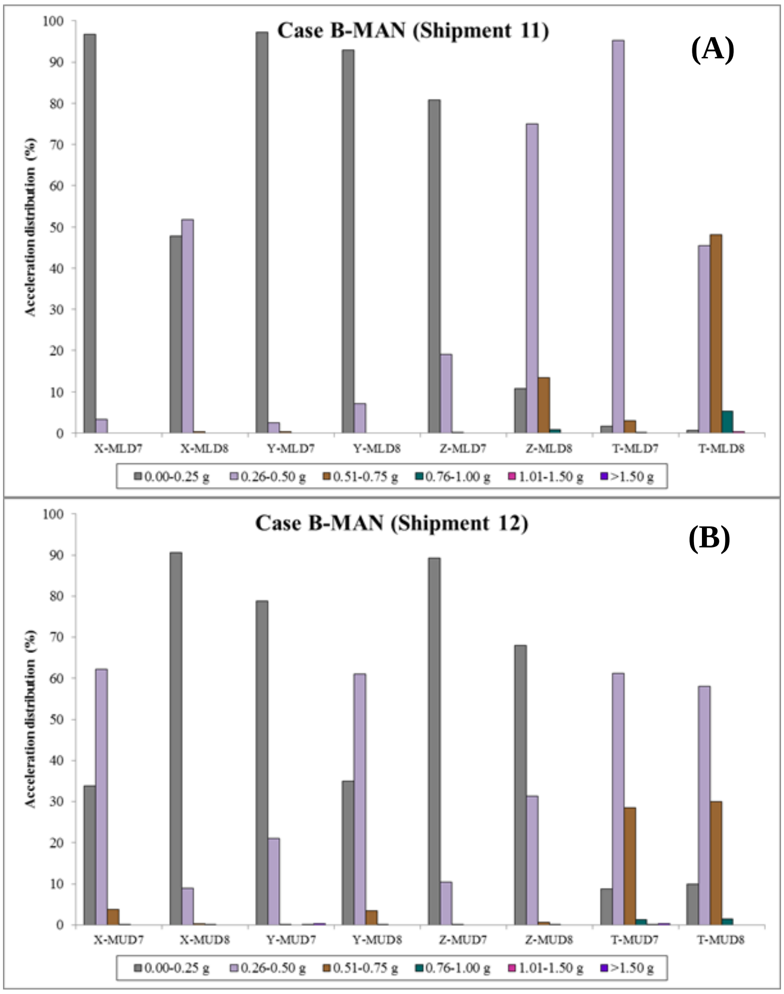


Figure 6.21: Acceleration distribution (%) of X, Y, Z and T vibrations in case B from shipment 11 (C) and 12 (D) on the Manchestrer route. The position was encoded as middle (M) with pallet number.

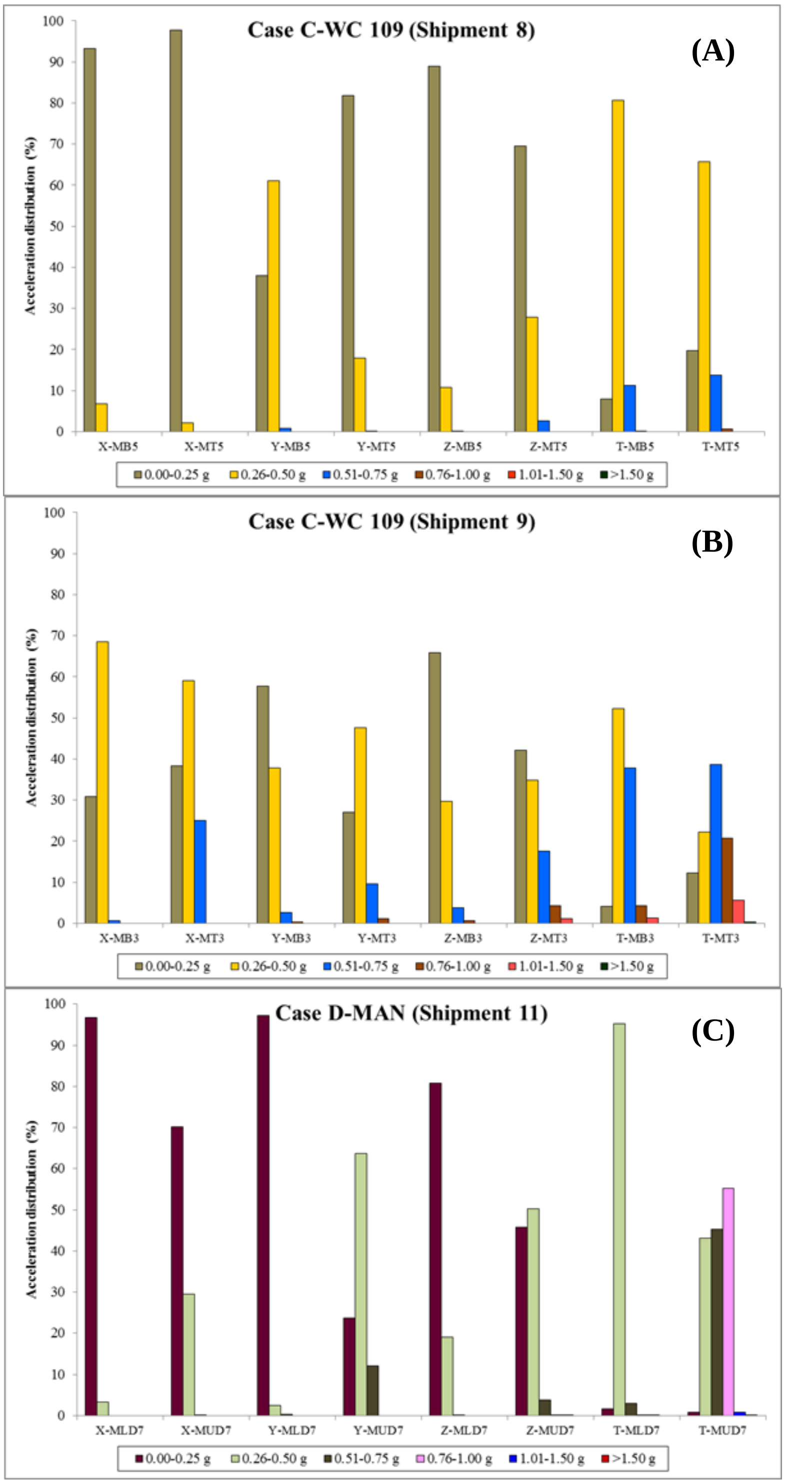


Figure 6.22: Acceleration distribution (%) of X, Y, Z and T vibrations in case C and D from shipment 8 (A), 9 (B) and 11 (C). The position was encoded as middle (M), upper deck (UP) and lower deck (LD) with pallet number.

6.4.3 Root mean square acceleration (g_{rms}) and a height of stacking during transport on the WC100, WC109 and Manchester routes

The acceleration (g) result was calculated and reported in terms of root mean square acceleration (g_{rms}) from the departure place to the arrival place. The location codes and details for unloading food product are reported in Appendices 1.1-1.10. The g_{rms} value and a height of stacking are described in each case study for the three routes of food shipments. In this study, the pallet height depended on the quantity of food products from the client requirements to be delivered and therefore varied in each shipment.

6.4.3.1 The g_{rms} and height of stacking in case A

Tables 6.6-6.8 show the result of pallet height and g_{rms} value in case A during travelling transport on the three routes. The height of the attached vibration logger also measured from the truck floor. The range of height level in case A on the WC100 route was 750 to 1300 mm, while the pallet height of the WC109 and Manchester shipments were 900-1350 mm and 1260-1830 mm, respectively.

The results of g_{rms} value were described for the four coordinates of vibration from the four cases. The g_{rms} values from three coordinates (X, Y and Z) varied on the shipment in each route. The results showed that vertical (Z-axis) and longitudinal (Y-axis) coordinates had the highest vibration levels for case A (approximate 50% of the total of 8 shipments) (Tables 6.7-6.10). In case A (WC100), for vertical (Z-axis) and total vibration (T-axis) directions, the rear position from shipment 1 and 3 notably performed a higher g_{rms} value than the middle or front position. On the other hand, the lateral g_{rms} value (X-axis) at the front position of shipment 2 was greater than for the middle position (Tables 6.7 and 6.8).

Another result of the WC109 route (shipment 6 and 7), the rear position still had a higher g_{rms} value of the vertical and total vibrations than the front position (Table 6.9). These results from the WC100 and WC109 routes (city streets) also were similar to the Manchester shipment on highways by a refrigerated semi-trailer (Table 6.10). Therefore, the overall results for the rear position from vertical (Z-axis) and total (T-axis) coordinates show a strong vibration as compared to the middle or front positions for either a refrigerated truck or a refrigerated semi-trailer (Tables 6.7-6.10).

6.4.3.2 The g_{rms} and height of stacking in case B

In case B (left-right side), the range of stacking heights at the top position was approximately 1000-1400 mm (WC100), 900-1700 mm (WC109), and 1300-1700 mm (Manchester) (Tables 6.11-6.13). These stacking levels for case B were as high as those levels for case A (Tables 6.7-6.10).

For three of the routes (8 shipments), the vertical axis (Z-axis) was the main vibration for case B (left-right side) which was nearly accounted for 50% of the total shipments (Tables 6.11-6.13). In the WC100 shipment (the middle of a vehicle), the vertical (Z-axis) and total (T-axis) vibrations at right side were slightly higher g_{rms} levels than at the left side in all unloading places (Table 6.11). On the other hand, these results of vibrations from the WC100 shipment differed from the WC109 shipment. The right pallet at the front of a vehicle (shipment 5 and 7) and at the middle position (shipment 9) gave lower g_{rms} levels of those vibrations than the left pallet (Table 6.12). On the highway road to Manchester, the right pallet had the highest g_{rms} levels of those vibrations in shipment 11 (Table 6.13). Overall, the different g_{rms} of vibration levels between right and left sides were not consistent and depended on the transport route and the position in the vehicle.

Table 6.7: The g_{rms} values of lateral and longitudinal vibrations in case A (front, middle and rear positions) on the WC100 route (periods of loading and unloading not included).

Shipment	Unloading	Height of the attached logger (mm)	Lateral vibration (X) g_{rms}			Longitudinal vibration (Y) g_{rms}		
			Front	Middle	Rear	Front	Middle	Rear
1	L0-L1	M5=1000 R9=1050	nd	0.32	0.34	nd	0.30	0.25
	L1-L2		nd	0.28	0.33	nd	0.31	0.28
	L2-L3		nd	0.30	0.30	nd	0.28	0.26
2	L0-L1	F1=1300 M5=1250	0.32	0.18	nd	0.23	0.39	nd
	L1-P2		0.43	0.26	nd	0.33	0.43	nd
	L2-L3		0.39	0.22	nd	0.29	0.38	nd
	L3-L4		0.31	0.18	nd	0.23	0.30	nd
	L4-L5		0.12	0.05	nd	0.11	0.11	nd
3	L0-L1	F1=1260 M5=750 R11=950	0.23	0.29	0.18	0.25	0.28	0.37
	L1-L2		0.27	0.30	0.21	0.32	0.30	0.36

nd is not determined owing to having only 3 loggers for each case.

Table 6.8: The g_{rms} values of vertical and total vibrations in case A (front, middle and rear positions) on the WC100 route (periods of loading and unloading not included).

Shipment	Unloading	Height of the attached logger (mm)	Vertical vibration (Z) g_{rms}			Total vibration (T) g_{rms}		
			Front	Middle	Rear	Front	Middle	Rear
1	L0-L1	M5=1000 R9=1050	nd	0.43	0.37	nd	0.46	0.56
	L1-L2		nd	0.49	0.48	nd	0.53	0.65
	L2-L3		nd	0.42	0.38	nd	0.47	0.55
2	L0-L1	F1=1300 M5=1250	0.17	0.17	nd	0.43	0.47	nd
	L1-P2		0.29	0.33	nd	0.61	0.61	nd
	L2-L3		0.29	0.25	nd	0.56	0.50	nd
	L3-L4		0.17	0.21	nd	0.42	0.41	nd
	L4-L5		0.22	0.25	nd	0.52	0.47	nd
3	L0-L1	F1=1260 M5=750 R11=950	0.20	0.22	0.32	0.40	0.46	0.52
	L1-L2		0.29	0.32	0.46	0.51	0.53	0.62

nd is not determined owing to having only 3 loggers for each case.

Table 6.9: The g_{rms} values of lateral, longitudinal, vertical and total vibrations in case A (front, middle and rear positions) on the WC109 route (periods of loading and unloading not included).

Shipment	Unloading	Height of the attached logger (mm)	Lateral vibration (X) g_{rms}			Longitudinal vibration (Y) g_{rms}		
			Front	Middle	Rear	Front	Middle	Rear
4	L0-L1	F1=1100 M5=900 R7=1200	0.23	0.23	0.28	0.28	0.51	0.32
	L1-L2		0.25	0.26	0.33	0.33	0.62	0.35
6	L0-L1	F1=1260 R10=1320	0.27	nd	0.22	0.28	nd	0.31
7	L0-L1	F1=1240 M5=1350 R7=1300	0.38	0.26	0.24	0.29	0.29	0.24
			Vertical vibration (Z) g_{rms}			Total vibration (T) g_{rms}		
			Front	Middle	Rear	Front	Middle	Rear
4	L0-L1		0.18	0.21	0.29	0.41	0.59	0.52
	L1-L2		0.42	0.26	0.34	0.64	0.72	0.59
6	L0-L1		0.18	nd	0.27	0.43	nd	0.47
7	L0-L1		0.27	0.28	0.38	0.55	0.58	0.51

nd is not determined owing to having only 3 loggers for each case.

Table 6.10: The g_{rms} values of lateral, longitudinal, vertical and total vibrations in case A (front, middle and rear positions) on the Manchester route (periods of loading and unloading not included).

Shipment	**Unloading**	**Height of the attached logger (mm)**	**Lateral vibration (X) g_{rms}**			**Longitudinal vibration (Y) g_{rms}**		
			Front	**Middle**	**Rear**	**Front**	**Middle**	**Rear**
10	L0-L1	F5=1830 MLD7=1480 RLD15=1260	0.17	0.19	0.35	0.19	0.24	0.16
12	L0-L1	MUD7=1300 RUD15=1680	nd	0.36	0.38	nd	0.27	0.40
			Vertical vibration (Z) g_{rms}			**Total vibration (T) g_{rms}**		
			Front	**Middle**	**Rear**	**Front**	**Middle**	**Rear**
10	L0-L1		0.16	0.36	0.52	0.30	0.54	0.68
12	L0-L1		nd	0.22	0.29	nd	0.50	0.62

nd is not determined owing to having only 3 loggers for each case.

6.4.3.3 The g_{rms} and height of stacking in case C and D

The top and bottom (case C) levels of pallet were studied only for the middle position of the vehicle (WC109). The different height between the bottom level and the top level was 880 mm (shipment 8) and 1200 mm (shipment 9). In the shipment 9, the top level of stacking had the higher g_{rms} levels of vertical (Z-axis) and total (T-axis) vibrations than the bottom level (Table 6.14). In addition, in case D, the upper deck of a semi-trailer on the Manchester route shows the higher g_{rms} levels of those vibrations than the lower deck with the height level of 1400 mm (Table 6.12). The g_{rms} results of both case studies (C and D) show a higher position in the pallet or deck caused the increase of vibration levels.

6.4.3.4 Payload (% total loaded pallets) in the single drop and multiple drop deliveries

In the case of a single drop delivery, the London shipments from WC100 and WC109 were selected as a percentage of total loaded pallets (%). The shipment 4 and 9 (50% of total loaded pallets) had higher g_{rms} values of T-axis (0.52 to 0.62 *g*) than shipment 6 and 8 (79-86% of total loaded pallets) (0.25 to 0.51 *g*) (Tables 6.9 and 6.12). In the case of multi drop deliveries, the g_{rms} values of all four axes gradually increased after unloading pallets when compared with the initial g_{rms} values (L0-L1), for example, shipment 3 (WC100), and shipment 4 and 9 (WC109) (Table 6.6-6.8). Therefore, less loaded pallets notably resulted in an increase vibration level (g_{rms} value) of all three positions.

Table 6.11: The g_{rms} values of lateral, longitudinal, vertical and total vibrations in case B (left and right positions) on the WC100 route (periods of loading and unloading not included).

Shipment	Unloading	Height of the attached logger (mm)	Lateral vibration (X) g_{rms}		Longitudinal vibration (Y) g_{rms}		Vertical vibration (Z) g_{rms}		Total vibration (T) g_{rms}	
			Left	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**
1	L0-L1	M5=1000 M6=1020	0.27	0.32	0.28	0.30	0.26	0.43	0.46	0.61
	L1-L2		0.27	0.28	0.27	0.31	0.37	0.49	0.53	0.64
	L2-L3		0.28	0.30	0.27	0.28	0.27	0.42	0.47	0.59
	L3-L4		0.28	0.30	0.26	0.34	0.34	0.48	0.52	0.62
	L4-L5		0.21	0.26	0.22	0.19	0.19	0.19	0.36	0.39
2	L0-L1	M5=1250 M6=1340	0.18	0.23	0.39	0.17	0.17	0.41	0.47	0.57
	L1-P2		0.26	0.31	0.43	0.33	0.33	0.65	0.61	0.83
	L2-L3		0.22	0.30	0.38	0.25	0.25	0.58	0.50	0.74
	L3-L4		0.18	0.24	0.30	0.21	0.21	0.30	0.41	0.44
	L4-L5		0.22	0.26	0.34	0.25	0.25	0.33	0.47	0.54

Table 6.12: The g_{rms} values of lateral, longitudinal, vertical and total vibrations in case B (left and right positions) on the WC109 route (periods of loading and unloading not included).

Shipment	**Unloading**	**Height of the attached logger (mm)**	**Lateral vibration (X) g_{rms}**		**Longitudinal vibration (Y) g_{rms}**		**Vertical vibration (Z) g_{rms}**		**Total vibration (T) g_{rms}**	
			Left	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**
5	L3-L4	F1=1400 F2=1650	0.20	0.20	0.27	0.21	0.19	0.17	0.39	0.34
	L4-L5		0.21	0.22	0.22	0.22	0.18	0.25	0.36	0.40
7	L1-L2	F1=1240 F2=1400	0.41	0.23	0.33	0.28	0.32	0.21	0.61	0.42
	L2-L3		0.42	0.25	0.35	0.30	0.40	0.25	0.68	0.47
8	L0-L1	M5=1380 M6=1260	0.13	0.19	0.15	0.21	0.15	0.19	0.25	0.24
9	L0-L1	M3=1700 M4=900	0.32	0.27	0.38	0.41	0.42	0.26	0.65	0.55
	L1-L2		0.33	0.27	0.38	0.40	0.46	0.27	0.68	0.56
	L2-L3		0.32	0.28	0.41	0.40	0.48	0.31	0.71	0.57

Table 6.13: The g_{rms} values of lateral, longitudinal, vertical and total vibrations in case B (left and right positions) on the Manchester route (periods of loading and unloading not included).

Shipment	**Unloading**	**Height of the attached logger (mm)**	**Lateral vibration (X) g_{rms}**		**Longitudinal vibration (Y) g_{rms}**		**Vertical vibration (Z) g_{rms}**		**Total vibration (T) g_{rms}**	
			Left	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**
11	L3-L4	LD7=1400 LD8=1650	0.22	0.30	0.18	0.23	0.25	0.45	0.38	0.58
12	L1-L2	UD7=1240 UD8=1400	0.36	0.25	0.27	0.36	0.22	0.27	0.50	0.51

Table 6.14: The g_{rms} values of lateral, longitudinal, vertical and total vibrations in case C (bottom and top positions) on the WC109 route and in case D (lower and upper decks) on the Manchester route (periods of loading and unloading not included).

Shipment	**Unloading**	**Height of the attached logger (mm)**	**Lateral vibration (X) g_{rms}**		**Longitudinal vibration (Y) g_{rms}**		**Vertical vibration (Z) g_{rms}**		**Total vibration (T) g_{rms}**	
			Bottom	**Top**	**Bottom**	**Top**	**Bottom**	**Top**	**Bottom**	**Top**
Case C										
8	L0-L1	MT5=1380 MB5=550	0.18	0.17	0.31	0.23	0.18	0.27	0.41	0.39
	L1-L2		0.19	0.19	0.29	0.19	0.15	0.18	0.38	0.33
	L2-L3		0.19	0.19	0.30	0.20	0.17	0.24	0.40	0.37
	L3-L4		0.21	0.20	0.31	0.24	0.21	0.27	0.43	0.41
9	L0-L1	MT3=1700 MB3=500	0.33	0.32	0.29	0.38	0.28	0.42	0.52	0.65
	L1-L2		0.34	0.33	0.32	0.38	0.32	0.46	0.57	0.68
	L2-L3		0.34	0.32	0.26	0.41	0.27	0.48	0.51	0.71
Case D			**Lower**	**Upper**	**Lower**	**Upper**	**Lower**	**Upper**	**Lower**	**Upper**
11	L1-L2	MLD7=1320 MUD7=1460	0.22	0.28	0.18	0.40	0.25	0.38	0.38	0.59

6.4.4 Power density (PD) peak and PD frequency peak during transport on the WC100, WC109 and Manchester routes

The power density (PD) value was analysed and presented in terms of PD peak (G^2/Hz) and PD frequency peak (Hz) which were classified on the basis of the frequency range (Hz) into 5-10 Hz and 11-25 Hz. It should be noted that the PD value for the London route was analysed from 5 to 20 Hz. The results were explained in each case for the different three routes.

6.4.4.1 Power density (PD) peak and PD frequency peak in case A

As shown in Table 6.15, the results of PD peak and PD frequency peak were compared in the three different positions (front, middle and rear pallets) in a refrigerated truck or semi-trailer. Also, the PD spectra of three positions at the top of the pallet showed a change profile from 5 Hz through 25 Hz (Appendices 2.1and 2.2). At the range of 11-25 Hz, the rear position gave the greatest PD peak value in the shipment 1 and 3 (WC100), 6 and 7 (WC109), and 10 (Manchester) when compared with either the middle or front position for the total of 8 shipments. These results also agreed with those higher g_{rms} values at the rear position (Table 6.10). The variation of PD frequency peak depended on the positions in vehicle, route and size of vehicle. In the food transport by the refrigerated trucks (18 and 26 tonnes), the PD frequency peak in the range of 5-10 Hz and 11-25 Hz was found in the overall frequency at 10 Hz and 11-14 Hz, respectively. In contrast, the frequency peak of the semi-trailer transport (44 tonnes) on the Manchester route differed from the refrigerated trucks (18 and 26 tonnes). At the range of 11-25 Hz, the peak value of PD frequency was at 19 or 21 Hz in the semi-trailer which was higher than for the refrigerated trucks. The PD frequency peak particularly varied with the deck position in the vehicle.

Table 6.15: Power density (PD) peak and PD frequency peak of case A during transport on WC100, WC109 and the Manchester routes.

Case/ Route	Shipment	Pallet Position	PD peak (G^2/Hz)		PD frequency peak (Hz)	
			Frequency range (Hz)		Frequency range (Hz)	
			5-10 Hz	11-25 Hz*	5-10 Hz	11-25 Hz*
A	1	M5	$8.10x10^{-4}$	$1.38x10^{-3}$	10	14
WC100		R9	$9.40x10^{-4}$	$1.89x10^{-3}$	10	14
	2	F1	$1.92x10^{-3}$	$2.30x10^{-3}$	10	11
		M5	$9.40x10^{-4}$	$2.05x10^{-3}$	10	13
	3	F1	$1.94x10^{-3}$	$2.16x10^{-3}$	10	12
		M5	$6.00x10^{-4}$	$8.09x10^{-4}$	10	14
		R11	$1.29x10^{-3}$	$3.14x10^{-3}$	10	13
WC109	4	F1	$1.01x10^{-3}$	$1.17x10^{-3}$	10	11
		M5	$1.18x10^{-3}$	$3.85x10^{-3}$	10	14
		R7	$9.80x10^{-4}$	$2.19x10^{-3}$	5	14
	6	F1	$5.40x10^{-4}$	$1.95x10^{-3}$	10	12
		R10	$1.27x10^{-3}$	$2.12x10^{-3}$	10	14
	7	F1	$2.05x10^{-3}$	$3.42x10^{-3}$	10	11
		M5	$1.47x10^{-3}$	$4.12x10^{-3}$	10	14
		R7	$8.20x10^{-4}$	$6.02x10^{-3}$	7	14
Manchester	10	F5	$5.40x10^{-4}$	$5.20x10^{-4}$	8	11
		M7-LD	$2.26x10^{-3}$	$2.16x10^{-3}$	8	14
		R15-LD	$8.80x10^{-4}$	$2.78x10^{-3}$	10	21
	12	M7-UD	$1.47x10^{-3}$	$2.15x10^{-3}$	7	19
		R15-UD	$2.79x10^{-3}$	$2.03x10^{-3}$	5	19

* The PD peak of the London route (WC100 and WC109) was analysed from 11 to 20 Hz.

6.4.4.2 Power density (PD) peak and PD frequency peak in case B

In the case of left and right pallets for the total of 8 shipments, at the range of 11-25 Hz, the right pallet at the middle or front position in the truck had a higher PD peak value than the left pallet. These above results were shown in the shipment 1 and 2 (WC100), 5 and 8 (WC109) and 11 (Manchester) (Table 6.16, Appendices 2.3 and 2.4). On WC109 route, the results of the PD peak on the right pallet differed from the g_{rms} value, which was a high level on the left side (Table 6.12). Overall, the PD frequency peak at 5-10 Hz and 11-25 Hz in case B agreed with case A for the three routes (Tables 6.16 and 6.17).

Table 6.16: Power density (PD) peak and PD frequency peak of case B during transport on the WC100, WC109 and the Manchester routes.

Case /Route	Shipment	Pallet Position	PD peak (G^2/Hz)		PD frequency peak (Hz)	
			Frequency range (Hz)		Frequency range (Hz)	
			5-10 Hz	11-25 Hz*	5-10 Hz	11-25 Hz*
B	1	M5	$7.10x10^{-4}$	$1.84x10^{-3}$	10	14
WC100		M6	$6.70x10^{-4}$	$2.91x10^{-3}$	10	14
	2	M5	$1.92x10^{-3}$	$2.05x10^{-3}$	10	13
		M6	$1.28x10^{-3}$	$3.92x10^{-3}$	10	14
WC109	5	F1	$5.80x10^{-4}$	$7.50x10^{-4}$	10	18
		F2	$8.30x10^{-4}$	$8.10x10^{-4}$	10	11
	7	F1	$7.10x10^{-4}$	$1.01x10^{-3}$	10	14
		F2	$1.53x10^{-3}$	$6.70x10^{-4}$	10	11
	8	M5	$7.30x10^{-4}$	$9.00x10^{-4}$	10	11
		M6	$1.53x10^{-3}$	$1.82x10^{-3}$	10	11
	9	M3	$3.06x10^{-3}$	$5.73x10^{-3}$	10	12
		M4	$1.47x10^{-3}$	$2.17x10^{-3}$	10	14
Manchester	11	M7-LD	$3.90x10^{-4}$	$3.90x10^{-4}$	10	11
		M8-LD	$1.45x10^{-3}$	$4.87x10^{-3}$	8	14
	12	M7-UD	$1.47x10^{-3}$	$2.15x10^{-3}$	7	19
		M8-UD	$2.05x10^{-3}$	$2.10x10^{-4}$	6	19

* The PD peak of the London route (WC100 and WC109) was analysed from 11 to 20 Hz.

6.4.4.3 Power density (PD) peak and PD frequency peak in case C and D

As shown in Table 6.17 and Appendix 2.5, the top package in the middle position had a greater PD peak value than the bottom package while the upper deck position also gave a higher PD peak value than the lower deck. From all cases on the Manchester route, there was a wide range of PD frequency peak from 5 to 25 Hz, especially case A (front, middle and rear positions) and case D (lower and upper decks). At a frequency of 5-10 Hz, the PD frequency peak from the semi-trailer (5 to 8 Hz) was less than from the truck (10 Hz). At a higher frequency (11-25 Hz), the PD frequency peak from the semi-trailer (11 to 21 Hz) was higher than from the truck (11-14 Hz).

Table 6.17: Power density (PD) peak and PD frequency peak of case C and D during transport on the WC109 and the Manchester routes.

Case	Shipment	Pallet Position	PD peak (G^2/Hz)		PD frequency peak (Hz)	
			Frequency range (Hz)		Frequency range (Hz)	
			5-10 Hz	11-25 Hz*	5-10 Hz	11-25 Hz*
C	8	M5-B	$2.60x10^{-4}$	$3.30x10^{-4}$	10	12
		M5-T	$7.30x10^{-4}$	$9.00x10^{-4}$	10	11
	9	M3-B	$2.65x10^{-3}$	$2.49x10^{-3}$	10	11
		M3-T	$3.06x10^{-3}$	$5.73x10^{-3}$	10	12
D	11	M7-LD	$3.90x10^{-4}$	$3.90x10^{-4}$	10	11
		M7-UD	$3.94x10^{-3}$	$1.18x10^{-3}$	6	19

* The PD peak of the London route (WC100 and WC109) was analysed from 11 to 20 Hz.

6.4.5 Air temperature profiles during transport on the WC100, WC109 and Manchester routes

For all case studies and shipments, the monitoring of air temperature was in the same position as for an actual vibration logger during transport. The monitoring temperature could not be determined on WC109 route at the front position (shipment 4) and case B (shipment 5 and 7) causing to a technical difficulty. The time duration of food shipment is shown on the horizontal axis (x) on the line graph, which also indicates the arrival time and finishing time for unloading. The location and unloading details are also reported in Appendices 1.1-1.10.

The temperature set point of the refrigerated truck and semi-trailer was 3^{o}C during the food delivery for all 12 shipments. During transport from the Reynolds company (L0) to the first unloading place (L1), the transport time was approximately 40 min (2400 sec) (Appendices 1.1-1.10). The temperature for that period reduced to nearly 4^{o}C during a refrigerated truck transport on the London routes (WC100 and WC109) from a higher loading temperature, whereas the temperature during the Manchester transport varied in the range of 4-8^{o}C (Figures 6.23-6.26). It should be noted that the shipment 6 showed a high temperature level (9-12^{o}C) through to the first location (L1) (Figure 6.24B). During unloading product, an increase of air temperature was nearly 2-3^{o}C (Figures 6.23A-B and 6.25A-D).

The loading period of the food product for the London routes was 30-60 min while the loading time of the Manchester shipment was 120-150 min (2.00-2.30 hours). Therefore, on the Manchester route, the air temperature at the front section had the lowest temperature (4^{o}C) as it was nearest to the cooling unit when compared to the middle or rear sections (8^{o}C). In contrast, the front section of the London shipment gave the highest temperature (Figures 6.23B- C and 6.24B-C).

In case B (left and right sides), both of the loggers had a similar temperature profile. The right pallet showed a slightly higher temperature than the left pallet (Figures 6.25A-B and F). The top and bottom position (case C) also had a similar temperature level (Figures 6.26A and B), while the temperature at an upper deck level gave a higher fluctuation than a lower deck (Figure 6.25C).

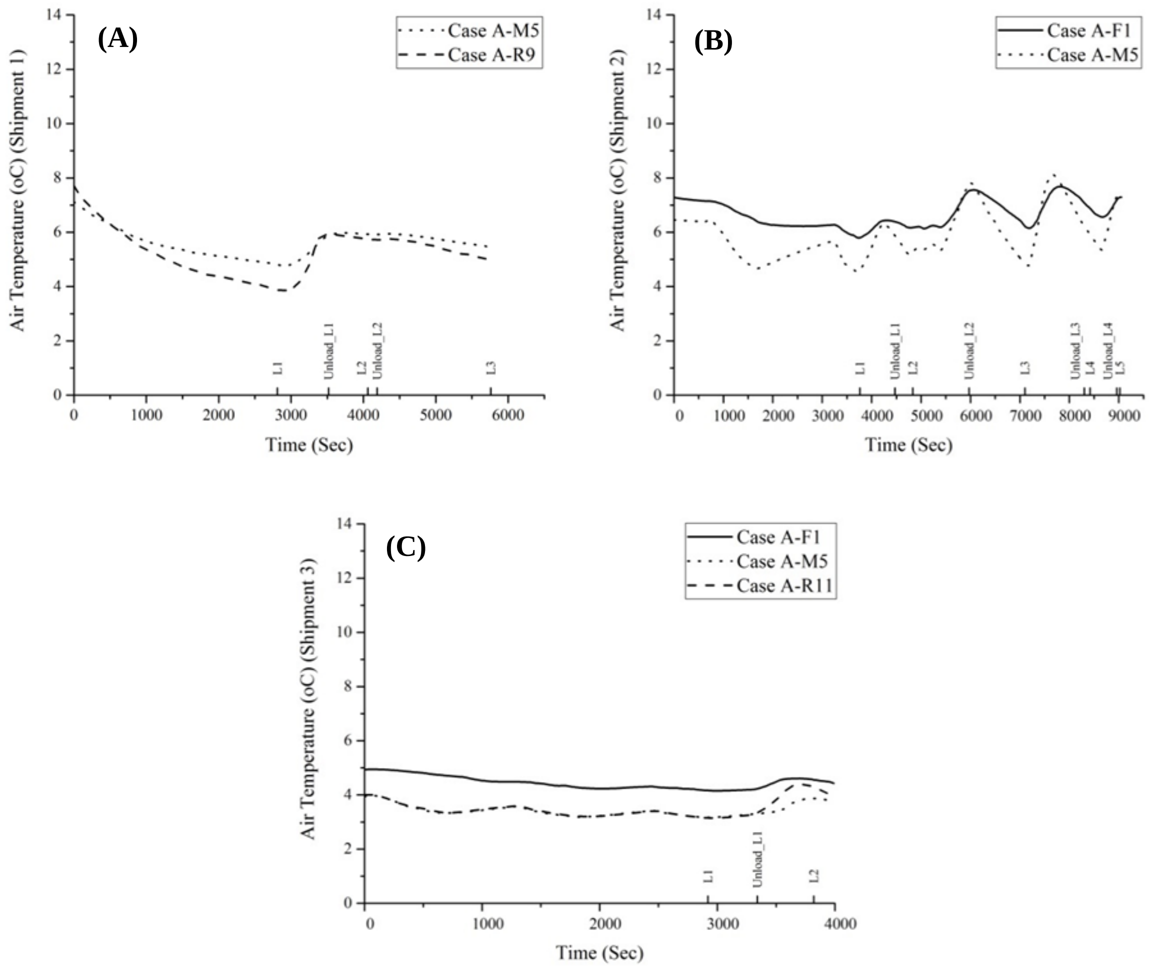


Figure 6.23: Air temperature in the refrigerated truck in case A from shipment 1 (A), 2 (B) and 3 (C) on the WC100 route.

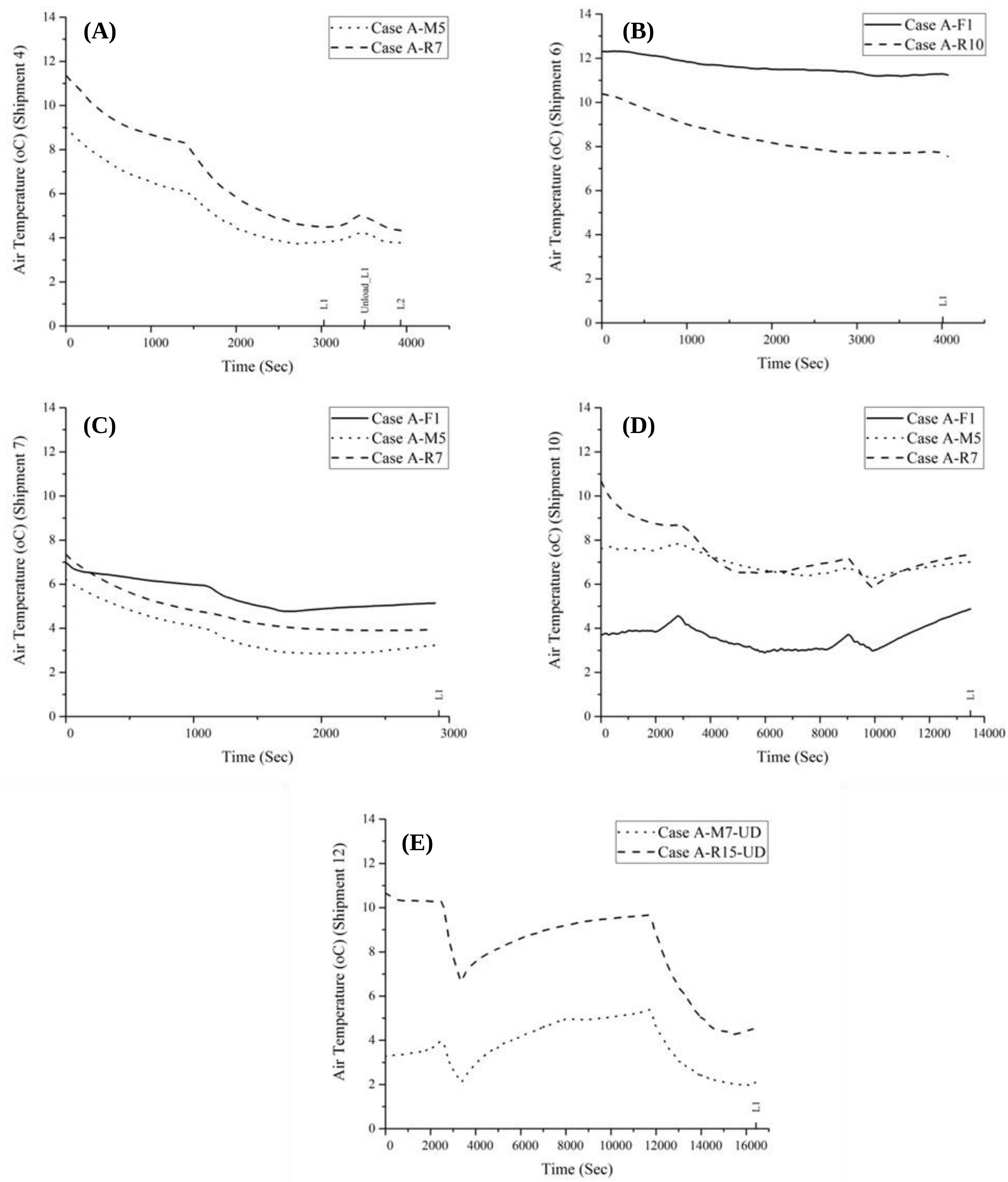


Figure 6.24: Air temperature in the refrigerated truck in case A from shipment 4 (A), 6 (B), 7 (C) 10 (D) and 12 (E). The shipments (4, 6 and 7) and (10 and 12) were studied on the WC109 and Manchester routes, respectively.

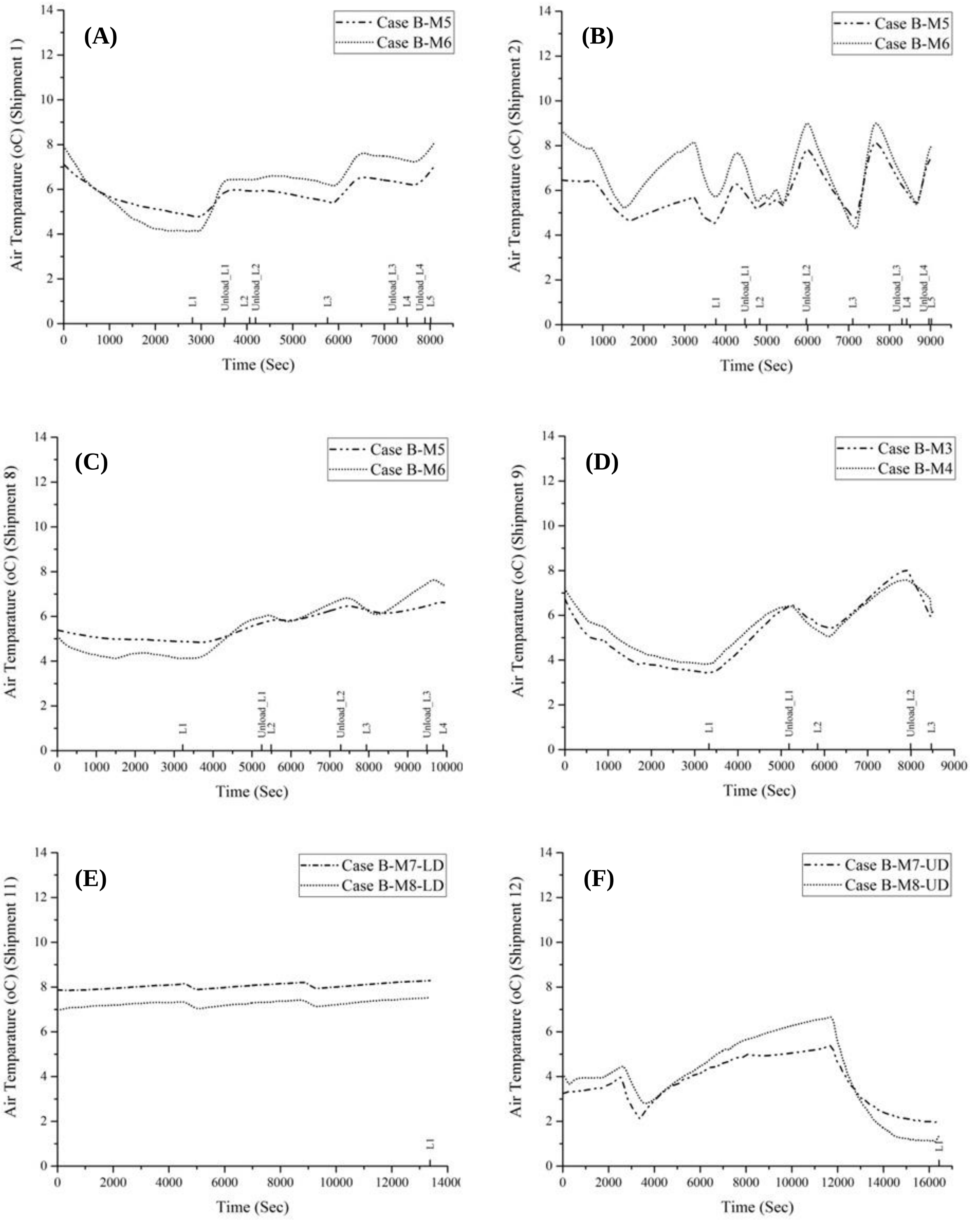


Figure 6.25: Air temperature in the refrigerated truck and semi-trailer in case B from shipment 1 (A), 2 (B), 8 (C), 9 (D), 11 (E) and 12 (F). The shipments (1-2), (8-9) and (11 and 12) were studied on the WC100, WC109 and the Manchester routes, respectively.

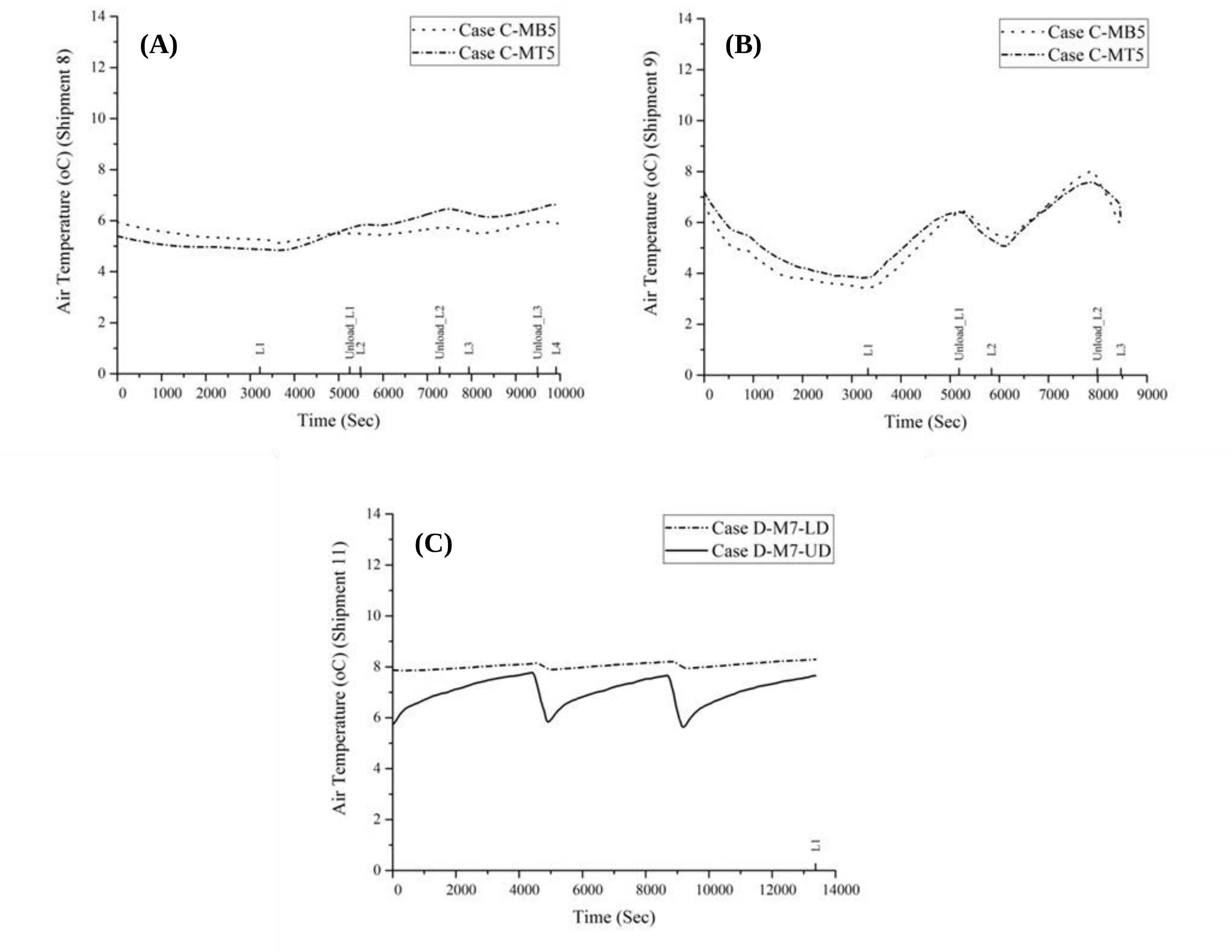


Figure 6.26: Air temperature in the refrigerated truck and semi-trailer in case C and D from shipment 8 (A), 9 (B) and 11 (C). The shipments (8, 9) and (11) were studied on the WC109 and Manchester routes, respectively.

6.5 DISCUSSION

6.5.1 Vehicle characteristics of the food transport on the London and Manchester routes

In this actual transport of food shipments on the London and Manchester routes, the experimental design was a survey research on the changes of vibration and temperature levels and could not replete in the exact same condition due to depending client requirement in each shipment of the mixed food load. Also, the number of vibration logger was limited for testing, including limited time of a company plan. Therefore, the results of this experiment could present a trend change of their levels in different positions of a refrigerated vehicle or a stack.

6.5.1.1 Speed of vehicle, vehicle size, travelling time and g_{rms} value

Several studies have linked vibration level and the transport operation such as speed (Rissi *et al.*, 2008), vehicle size (Jarimopas *et al.*, 2005) and type of suspension (Garcia-Romeu-Martinez *et al.*, 2008; Singh *et al.*, 2006) and payload (Garcia-Romeu-Martinez *et al.*, 2008). In the UK transport, the speed limit of goods vehicle over 7.5 tonnes in urban area is 48 km/hr and on highways 96-112 km/hr (The UK government, 2014). From the Reynolds company (L0) to the first or second unloading location (L1 or L2), the average higher truck speed (18 and 26 tonnes) on the London streets was 43-45 km/hr. A semi-trailer (44 tonnes) was used in the Manchester shipment on the highways with the average speed of the vehicle around 70 km/hr (Table 6.6).

When the delivery started from the first or second drop location, a reduced speed during food delivery was 20-30 km/hr on the London streets (WC100 and WC109) (Table 6.6). Zeebroeck *et al.* (2008) suggested that the range of speed (25-35 km/hr) should be an especial concern because these speeds may cause apple bruising at the position of 2000 mm behind the rear axle. In the current study, a lower speed of truck (20-30 km/hr) may cause fruit damage during food delivery on the London streets. However, the drivers for all food shipments controlled the speed of trucks and semi-trailers to below the limits for food delivery. According to departure time for the shipment in early morning at around 5:00 pm, the driver increased the truck speed from the company to the first unloading location to avoid busy roads during food delivery, which showed the maximum speed of truck (43-45 km/hr) as close to the minimum speed limit of good vehicle.

The travelling time for the London shipments was 50-80 min for 50 km, while there was longer distance and time of over 220 min for 315 km on the Manchester route (Table 6.6). The transport on highways caused an increase of the fruit damage level because of the long transport time when compared with unmetalled roads (Çakmak *et al.*, 2010; Soleimani and Ahmadi, 2014). A long travelling time may cause fruit damage, even for the transport on the smooth surface road. Also, the type of suspension was considered the effect on vibration level. The semi-trailers with air ride suspension gave a higher range of g_{rms} value (Z-axis) (0.29-0.52 g) than truck shipments with leaf spring suspension (0.27-0.38 g) (Tables 6.7-6.10). On the other hand, Lu *et al.* (2010a) reported that at a speed of 45-59.9 km/hr of truck transport on a local road had a higher g_{rms} value than on highways, which was in agreement with Çakmak *et al.* (2010). Conversly, the results in the current study differed from other research, which reported a lower vibration level in air ride suspension (Garcia-Romeu-Martinez *et al.*, 2008; Hinsch *et al.*, 1993; Singh *et al.*, 2006; Timm *et al.*, 1996; Soleimani and Ahmadi, 2014; Zeebroeck *et al.*, 2008). The larger size of trucks gave higher vibration levels than the smaller trucks (Jarimopas *et al.*, 2005; Chonhenchob *et al.* 2012). Moreover, a higher speed with over 70 km/hr gave a higher vibration level (g_{rms} value) than a lower speed at 20-30 km/hr (Lu *et al*., 2010a). Thus, it is possible that a higher g_{rms} values of Z-axis (vertical vibration) in the Manchester shipment is a result of vehicle size and speed.

The rear position of the load has a higher possibility of product damage resulting in the need to travel slower. Surprisingly, the rush hour or a busy time should be considered for food delivery due to a lower truck speed. In the case of shipments with a long period of travel, the rear position of semi-trailer should be particularly avoided for the placement of perishable produces with high susceptibility to bruise damage.

6.5.1.2 Payload (% total loaded pallet) on the vibration level

The payload was presented as a percentage of total loaded pallets (%) and most of all shipments contained less than 100% payload on the London routes. On WC109 route from Reynolds (L0) to the first unloading location (L1), 50 % of total loaded pallets (shipment 4 and 9) showed a stronger g_{rms} value (Total vibration: T-axis) (0.52 to 0.65 *g*), while an increase of the loaded pallets (shipment 6 and 8) by 30% affected a reduction of g_{rms} value (T-axis) (0.25 to 0.51 *g*) (Tables 6.9 and 6.12). For the multi drop deliveries, the overall g_{rms} value from four axes gradually increased after pallets were unloaded at the first drop, for example, in shipment 3, 4 and 9 (Tables 6.8, 6.9 and 6.12). A higher load of shipment showed a reduced vibration level, which agreed with Garcia-Romeu-Martinez *et al.* (2008). The average of g_{rms} for the loaded truck (0.194 *g*) was less than for the unloaded truck (0.245 *g*) with the leaf spring suspension. Moreover, Zeebroeck *et al.* (2008) found that a fully loaded truck reduced up to 33 times bruise damage of apples as compared to the light and half-loaded trucks. Hence, the results from the current study showed less loading and multi drop deliveries led to an increase in vibration levels. This raises a concern of increased damage level for multiple drop deliveries. The front position (final unloading) should be avoided where possible for a long travelling time.

6.5.1.3 The effect of truck characteristics and transport operation on power density (PD) frequency peak

Most studies on vibration levels during transports have been investigated by monitoring the frequency peak of the PD spectrum in many countries. The lower peak of frequency was 2-4 Hz during the actual transports in Thailand (Chonhenchob *et al.*, 2012), Taiwan (Ishakawa *et al.*, 2009), China and the US (Hinsch *et al.*, 1993; Zhou *et al.*, 2007). The frequency peak of PD profile in Spain, Iran and the US was approximately 5 Hz (Garcia-Romeu-Martinez *et al.*, 2008; Soleimani and Ahmadi, 2014; Timm *et al.*, 1996), while a higher level with the range of 10-15 Hz was investigated in Italy, Japan and Turkey (Barchi *et al.*, 2002; Berardinelli *et al.*, 2005; Ishakawa *et al.*, 2009; Vursavus and Özgüven, 2004). The frequency peak value of PD spectrum related to the above-mentioned results from many countries, particularly at 10-14 Hz. In the UK shipment, however, at a lower frequency of 5-10 Hz, the overall frequency peaks of PD spectrum were 7 Hz (semi-trailer with air ride suspension) and 10 Hz (truck with leaf spring suspension), while those peaks in the range of 11-25 Hz were 11-14 Hz (truck) and 19 Hz (semi-trailer) (Tables 6.15-6.17). A frequency range of 10-14 Hz may cause bruise damage in various fruits such as strawberries (Fischer *et al*., 1992), tomatoes (Bello *et al.*, 2013), figs (Çakmak *et al.*, 2010), kiwifruits (Tabatabaekoloor *et al.*, 2013), apple (Vesuvius and Özgüven, 2004), pear (Acıcan *et al.*, 2007) and watermelon (Shahbazi *et al.*, 2010). A further study, which takes a higher frequency (10-14 Hz) into account, will need to be undertaken to study the simulated vibration of various fresh produce to bruise damage.

The three sources of vibration level from vehicle were suspension (3-4 Hz), tyres (15-20 Hz), and truck floor (40-55 Hz) (Singh *et al.*, 2006). The major source of vibration frequency in the current study mainly may derive from the tyres of trucks and semi-trailers with an inflation pressure of 105 psi. Also, the truck transport was found in either lower or higher frequency peak in the PD spectrum depending on different road conditions and vehicle size in each country. According to the higher overall frequency peak of PD profile, the UK shipment may present a better road condition or a higher efficient vehicle than other countries.

Regarding suspension type in the current study, the frequency peak of air ride suspension (7 Hz) was lower than for the spring leaf type (10 Hz) (Tables 6.15-6.16). Also, the frequency peak of air ride type at 1.5-3 Hz was lower than leaf spring suspension at 4-5 Hz (Garcia-Romeu-Martinez *et al.*, 2008; Soleimani and Ahmadi, 2014). The speed of vehicle also related to the frequency peak, which was reported in unmetalled and highway roads. The peak frequency of shipments on highway roads in Turkey, Spain, France and Italy were at around 15-18 Hz with the speed at 60-134 km/hr (Çakmak *et al.*, 2010; Barchi *et al*., 2002), which showed a lower frequency peak at 3 Hz with a lower speed at 25-30 km/hr (Çakmak *et al.*, 2010). In the current study, at a lower speed (28-44 km/hr), the predominant frequency at 14 Hz was found in the shipments for different positions (front-middle-rear) on both London routes. The top and bottom level had a lower predominate frequency at 11-12 Hz (Tables 6.15 and 6.16). At a higher speed of 75 km/hr on highways, the semi-trailer shipments had a range of frequency peaks from 11 to 14 Hz, which was a similar frequency to the truck transports, except at the rear position on lower deck at 21 Hz and an upper deck at 19 Hz (Tables 6.15-6.17). Interestingly, there has not been any published research on the vibration frequency on the upper deck floor of semi-trailers. Furthermore, the speed of the vehicle may have less effect on frequency peak than vehicle size and position in the vehicle, which showed a strong frequency in semi-trailer at a rear position on the upper deck. The frequency peak of PD spectrum had less variation from the speed of different vehicle sizes than acceleration level (g_{rms} value). However, further investigation should be undertaken to monitor a frequency peak of semi-trailer shipment due to a high vibration level in each floor.

6.5.2 The effect of position in vehicle and package position in the stack on vibration level

The evaluation of vibration level was carried out in different positions in the vehicles, namely, case A (front, middle and rear positions), case B (left and right sides), case C (top and bottom levels) and case D (upper and lower decks). The g_{rms} values of the three coordinates (X, Y and Z axes) were considered in each case study for the three routes. The overall highest g_{rms} value was in the vertical direction (Z-axis), followed by the longitudinal direction (Y-axis) during transport on the London and Manchester routes (Tables 6.7-6.10). These results were in agreement with previous studies by other researchers, which showed the vertical vibration (Z-axis) gave the greatest vibration level during transport by truck, van and rail (Chonhenchob *et al.*, 2009, 2010, 2012; Lu *et al.*, 2010a; Rissi *et al.*, 2008). Thus, the primary importance of physical factors was indicated to the determination of vibration level in the actual transport such as intensity (power density: PD), frequency, the direction and the exposure time (Soleimani and Ahmadi, 2014). However, the variable factors of the current study were highly differentiated from the previous studies because of the mixed load and multi drop deliveries, not only a single product and delivery. The mixed load of the current study showed a wide range of food products in each package. Also, the main types of package were corrugated fibreboard box, common footprint tray and plastic crate without an exact pattern for stacking on pallets. The protection from vibration was using a shrink film to tightly wrap a load stack. Even on the same route and drop location, it was not always with the same condition of pallet, as this depended on client requirements. Thus, stack height was only a controlled factor of the mixed load in each shipment. Moreover, in the case of multi drop deliveries, it may be important to take the account of the route with clients that have a delivery which is more sensitive to damage. However, the geography of the whole route is probably more important.

6.5.2.1 The vibration level in case A (front, middle and rear positions)

In the food transport on the London and Manchester routes with a total of 8 shipments, the rear position of the trucks and semi-trailers gave a notably stronger g_{rms} level of vertical (Z-axis) and total (T-axis) coordinates than at the middle and front positions (Tables 6.7-6.10). These current results agreed with a higher PD value (Table 6.15) and *g* value over 0.50 *g* of the acceleration distribution (%) (Figures 6.15-6.17). For the Manchester shipments, the rear position in both upper and lower decks had around 50 % of the total acceleration within the range of 0.51-0.75 *g* (Figure 6.17). The results of the current study agreed with many previous studies. The rear position of the vehicle gave the highest g_{rms} value level when compared with either middle or front position during transport in Italy, the US and Iran (Berardinelli *et al.*, 2005; Hinsch *et al.*, 1993; Soleimani and Ahmadi, 2014) as much as the peak PSD spectra at the rear position (Zhou *et al.*, 2007; Barchi *et al.*; 2002). Thompson and Mitchell (2002) reported that the vibration damage is caused by a greater exposure of acceleration of gravity (1 *g*) than one time. In the current study, the highest percentage of *g* value (T-axis) was in the range of 0.26-0.50 *g*. At acceleration over 1.00 *g*, the overall shipments at the rear position gave less than 10 % of the acceleration distribution (Figures 6.15-6.17). In the case of a single drop, the front position was recommended for a package of fresh produce to highly susceptible damage rather than the middle and rear position. However, in the case of the multi drop deliveries, the front position may increase bruising damage due to a gradual vibration level with a long travelling time.

6.5.2.2 The vibration level in case B (left and right sides)

Until recently, there has been little published research on the different vibration level between left and right pallets. The case B was focused on the middle position of the vehicle to monitor vibration levels from 8 shipments. The greatest range of acceleration (*g*) was found in 0.26-0.50 *g* (Figures 6.18-6.21), which was similar to that highest percentage distribution of acceleration (*g*) value in case A (Figures 6.15-6.17). The acceleration (*g*) and g_{rms} values between right and left pellets were nearly the similar level and accounted for 50% of total 8 shipments (Figures 6.18-6.21), whereas the PD values of both sides was a similar value for 25 % of total 8 shipments (Appendix 2.3A, B). The tendency of results from the current study agreed with the previous study by Timm *et al.* (1996). The peak PSD levels of the left and right sides of the vehicle were not different with air ride suspension at similar frequencies at 4 and 20 Hz. However, in the current study, the variation of vibration level in left and right sides may depend on the transport route, weight of the loaded pallet and road conditions. It may be that road surfaces, particularly in London shipments vary, with manholes, for instance, almost always being on the left hand side. According to a limited publication in this case and inconsistent results, considerably more confirmation will need to be done to determine the vibration level between left and right positions.

6.5.2.3 The vibration level in case C (top and bottom level) and case D (upper and lower decks)

In the middle position of the vehicle, the vibration level between the top and bottom levels of pallet was investigated with different heights by 880-1200 mm. In preparation for food shipment, the stack in each pallet was tightly wrapped with a shrink film to protect the package drop and could reduce the package movement. The top package of stacking had the greatest vibration level (g_{rms}), followed by the centre and bottom levels (Barchi *et al.*, 2002; Berardinelli *et al.*, 2005;

Hinsch *et al.*; 1993, Ranathunga *et al.*, 2010*;* Soleimani and Ahmadi, 2014; Slaughter *et al.*, 1993). As expected, the top level of pallet gave a higher acceleration (*g*) level (>0.76 *g*) than the bottom level (Figure 6.22B). Interestingly, case D (upper and lower deck at middle location) has not been recorded in published research that was a new condition. The upper deck floor showed a greater *g* value than the lower deck floor with a range of acceleration from 0.51 to 1.00 *g* (Figure 6.22C), including greater g_{rms} levels (Z-axis and T-axis) (Tables 6.14) and PD peak value (Table 6.17).

There is a large volume of published studies in top and bottom levels of pallet relating the fruit damage from simulated vibration and actual transport. In the case of the simulated vibration, higher position of package on pallet gave higher bruises in watermelon and tomato (Shahbazi *et al.*, 2010; Bello *et al.*, 2013). Regarding the actual transport, the top package of a stack which contained strawberry or tangerine fruits also caused an increase mechanical damage (Aliasgarian *et al.*, 2013; Jarimopas *et al.*, 2005). In the current study, the top and rear positions gave a rise of vibration level during actual transport. Zhou *et al.* (2007) reported that the top reusable plastic crates (RPCs) of stacking at the rear position gave the greatest mechanical damage to 'Huanghua' pear surface when compared with in the front-top RPCs, and in the front and rear of bottom RPCs, respectively. In the current study, it is possible that top position at either front or rear position may give a rise to fruit damage more than the bottom position. By combining the effect of position to vibration level found in the current study, it is possible that top layer of the pallet at the rear position on the upper deck floor at may give the highest vibration level in the semi-trailer. Moreover, the vibration study in lower and upper decks was based on only a short trial because of a limitation of the company plan. It is recommended that further research should be undertaken to confirm the result of that position in semi-trailer on highways, including front position.

Overall, once the position in the vehicle is considered in the truck the information should be integrated with the susceptibilities to damage of the products to be transported. Most, if not all the other research studies that have been referred to throughout this dissertation are considering full loads of one product. The current study considers multi products which lead to cases of less than 100 % loading. Therefore, the location of specific products within the pallet and truck is particularly important. On the London route each pallet has a number of different products which makes the correct location from vibration consideration difficult to decide. However, on the Manchester route there are complete pallets of various products. Therefore, on this route the loading should very much take into account position and damage susceptibilities. In the current study, the rear-top position on the upper deck in semi-trailer may cause more severe fruit damage. For instance, strawberries should be located in the front and bottom positions for a food shipment in short and long deliveries by truck and semi-trailer due to less vibration level, particularly a single drop. Even the front position giving the less vibration level should be reconsidered in the case of a multi drop delivery and long travelling time during truck transport, which may increase damage than the middle and rear positions. A product like cabbage could be placed in either top or rear position where there is a stronger vibration level as this is a product that is not very susceptible to damage. However, positioning for low damage as mentioned above may have to be changed once temperature distribution is also factored in and this could form the basis for a more detailed study.

6.5.3 The effect of position in vehicle and package position in the a stack on temperature changes

The food delivery to retail and food service has a wide range of temperatures for mixed loads such perishable and non-perishable products in the same vehicle (LeBlanc and Hui, 2005). In the current study, the temperature set point of the refrigerated vehicles was 3^{o}C for all mixed load transit; however, the variable temperature in each route and position in the vehicle meant that initially it started around 4 to 8^{o}C (WC100), 4 to 12^{o}C (WC109) and 4 to 11^{o}C (Manchester). The temperature was reduced to nearly 4^{o}C at the first unloading location on the London routes for 40 min (2400 sec). For the entire food shipment, the temperatures were around 4 to 8^{o}C (London shipments) and 2 to 8^{o}C (Manchester shipments), except at 8-12^{o}C in shipment 6 (WC109) (Figures 6.23-6.26). Therefore, the overall temperature for food delivery (4 to 8^{o}C) was higher than the temperature set point by 3°C.The temperature range of 4-8°C also was optimum temperature for the various fruits and vegetables such as cucumber, potato (late crop), avocado, mandarin, tangerine, persimmon, pomegranate, pineapple, basil, aubergine, okra and lime (Thompson, 2002b).

6.5.3.1 The air temperature level in case A (front, middle and rear positions)

A top-air delivery or overhead system is commonly used in refrigerated semi-trailers. A number of studies have found that a uniformity of air distribution is found in the area from front to rear position and along the column (stack) (Hui *et al.*, 2006; Havey *et al.*, 1980; Rediers *et al.*, 2009; Pelletier *et al.*, 2011). In the current study, the total loaded pallets (50-100%) in the London shipments gave a temperature in the middle position at around 4°C, which was the lowest level as compared to the front and rear positions in both London shipments (30-60 min) by around 2°C (Figures 6.23 and 6.24). These results from the current study were similar to another report by Havey *et al.* (1980) who stated that the temperature of the middle load gave a lesser change and a cooler temperature than at load against the side wall in a truck shipment. Also, less airflow occurred in the middle section across the width and along the length (Hui *et al.*, 2006). Thompson *et al.* (2002) also supported that the middle-loaded position had a cooler air temperature than the side wall load by around 1.7 to 3°C. In the current study, therefore, the middle position showed a cooler temperature profile than the rear or front position by around 2°C due to less airflow in the middle area. For short travelling time, the food delivery on the city streets, it is suggested to arrange the pallets in the middle of the truck to have food products that require cooler temperature (sensitive to warm temperature) and tolerant of middle vibration level, such as dairy products, sweet corn, broccoli and cauliflower.

In the Manchester shipments with a full load for 220 min, the coolest temperature occurred in the front position at around 4°C when compared with middle and rear positions at around 8°C (Figure 6.24B) due to nearness to the refrigeration unit in the front with the longest loading time for 120-150 min. The low temperature at 4°C (front position) could be a concern for chilling-sensitive commodities such as banana, citrus, mango, pineapple, pomegranate, cucumber, aubergine, okra, and tomato (Thompson, 2002b). Even the period of exposure was only 3-4 hours (around 220 min), it may cause chilling injury. For instance, at the exposure temperature at 10°C for an hour, mature-green banana shows moderate chilling injury; moreover, the chilled banana has a higher sensitivity to mechanical injury (Kader, 2013). The low temperature (4°C) at front position should be suggested for the placement on non-chilling sensitive commodities such as apple, berry fruits, pear, persimmon, asparagus, broccoli, cabbage, carrot, lettuce, onion, and celery (Kader, 2002a).

6.5.3.2 The air temperature level in case D (upper and lower decks)

In the middle position of a semi-trailer, the upper deck floor showed an unstable temperature profile and had a cooler temperature when compared with the lower deck (Figure 6.26C). The refrigeration unit is located in the front-top position resulted in a lower temperature for the upper deck. The pattern of the temperature profile of the upper deck floor gradually increased and dropped rapidly by 2°C around every 5000 sec (1.30 hour), which showed a thermostat differential for automatically controlling refrigeration.

6.6 CONCLUSION

The variation of vibration levels was influenced by the vehicle and route properties. For vibration results, the semi-trailers on highway roads had higher vibration levels with a longer travelling time than the trucks on the city streets. The predominant frequency in a lower range of the frequencies (5-10 Hz) was at 7 Hz for a semi-trailer and at 10 Hz for a truck, whereas, a frequency of 11-14 Hz was often found in all shipments, except the frequency peak of PD at 19 Hz on the upper deck floor. In terms of the different positions, there was a higher vibration level at the rear position than either front or middle position from both refrigerated vehicles. The upper deck had higher levels of vibration for the semi-trailer. The top of the pallet was higher than the base. These differences should be taken into account when loading mixed products. There was not a consistent difference between right and left sides. The multi drop deliveries gave a gradual increase of vibration level after unloading pallets as well as a higher vibration level of less loading in the truck.

As regards temperature in the refrigerated truck or semi-trailer with a set point at $3^{o}C$, the entire food delivery or transport, the ranges of temperature during transport were around 4 to $8^{o}C$ in the London shipments and 2 to $8^{o}C$ in the Manchester shipments, except at 8 to$12^{o}C$ in shipment 6 (WC109). For the short delivery, the coolest temperature occurred in the middle position load of truck, whereas the front part of semi-trailer had the coolest temperature at around $4^{o}C$ for long travelling time. There were the similarly cool temperatures between top and bottom levels of stack, as well as left and right sides. The upper deck floor gave a lower temperature and was more unstable than the lower deck floor. For the long transport by semi-trailer, therefore, a cooler temperature at the front position required that the non-chilling-sensitive commodities were placed there.

By combining factors between vibration and temperature level in the different positions, it is possible that the front-bottom position is suggested to be allocated for the fruits and vegetables that are susceptible to bruising damage and require cooler temperatures in a semi-trailer on highways such as berry fruits, soft fruits, mushroom and fresh-cut produce. Moreover, the middle-bottom position is recommended for the placement on these fresh produces for the truck shipment.

CHAPTER 7

OVERALL DISCUSSION

7.1 INTRODUCTION

Strawberry fruits are very susceptible to impact and vibration forces incurred through the postharvest handling and transport from farm to retail store or supermarket. In a study of strawberry waste in the British strawberry supply chain, it was reported by Terry *et al.* (2011) that the strawberry losses at the stages from packing to retail market accounted for 4-6% of total strawberry losses (7.5-11.5%). Therefore, the packinghouse operation, transport and distribution procedures are important in affecting the strawberry bruises. However, the quality and mechanical damage of strawberries after harvesting were also influenced by the preharvest factors such as a cultural system, climate condition, cultivar, water relation and nutrition.

In this study, the two major experimental designs were carried out to study the two cultivation periods and postharvest factors affecting mechanical damage (impact and vibration bruises) and quality of British commercial strawberries at harvest and after cool storage. For the preharvest factors, the differing quality and bruise damages may depend on cultivars ('Elsanta' and 'Sonata') and the seasonal cultivations (winter and summer). In the current study of postharvest factors, there were simulated tests (impact and vibration trials) on both strawberries from the greenhouse production and the investigation of vibration and temperature levels during an actual food transport. In previous publications of the simulated studies, the effect of impact and vibration forces on an individual strawberry fruit were explored for either different drop heights or frequency/acceleration levels. Therefore, this current study set out to assess the simulated trials of impact and vibration tests on a whole strawberry punnet with various factors such as the drop height of the impact test and the frequency and exposure time of the vibration test.

Previous investigation of vibration levels during transport often focussed on a single product and a single drop delivery with a full load for the different positions in the vehicle. However, no research focussed on a mixed load with various products and packages for multi drop deliveries. There has been no study conducted on vibration level during food shipment in the UK. In an alternative approach to reduce strawberry bruise damages from impact and vibration, this study mainly investigated simulated tests in conjunction with the actual transport.

7.2 FACTORS INFLUENCING THE BRUISE DAMAGE AND QUALITY OF STRAWBERRY FRUIT AFTER IMPACT AND VIBRATION TESTS

Preharvest and postharvest factors affect the quality and susceptibility to bruise damage in 'Elsanta' and 'Sonata' strawberries, and these include the growing season, cultivar, impact and vibration forces, and temperature. The knowledge of factor analysis obtained in this current study, which is summarized in Figure 7.1, assists in the improvement of bruise assessment from the simulated impact and vibration tests. Understanding factors affecting bruise damage could be integrated into postharvest handling and transport management, in part by the simulated tests and the actual transport to reduce or protect bruise damage of strawberries and other soft fruits.

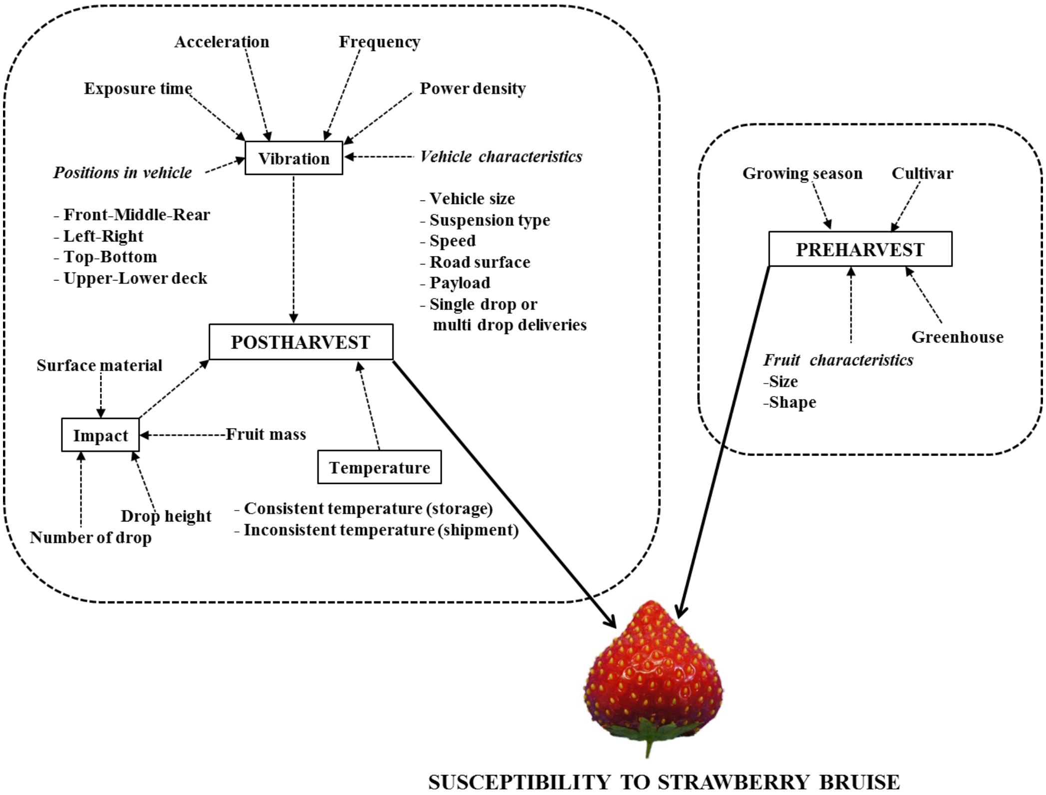


Figure 7.1: Overall factors influence on susceptibility to strawberry bruise. *Source*: Chaiwong (2015).

7.2.1 Growing season influencing strawberry bruise and quality

According to the first hypothesis of this dissertation, it is expected that there will be a higher level of impact and vibration damage on summer cultivation crops of ‘Elsanta’ and ‘Sonata’ cultivars (section 1.4, a) and this has been shown to be a valid hypothesis._Therefore, the effect of enhancing temperature in greenhouse production for ‘Elsanta’ and ‘Sonata’ strawberries on increasing susceptibility to bruise and quality was determined in 2014-2015. It should be noted that all cultivations used new strawberry plants in this study. In the summer cultivation, a range of higher temperatures (21 to 25°C) produced a shorter period for growth and development: around half the time (36 days) compared with the winter cultivation (8 to 21°C), producing smaller fruit and lower yield (section 4.5.1). Both the large (20 g) and medium (12 g) fruit sizes in the current study satisfied the marketing standard of ‘Extra class’ British strawberries with the equatorial section of 25 mm (Rural Payments Agency, 2014).

The considerations of quality attributes were: percentage of bruise damages (dry and wet bruises), electrical conductivity (EC), %TSS and %TA contents. The strawberries from the summer cultivation gave a higher bruise level than from the winter cultivation after impact and vibration tests, including a lower number of undamaged fruits without the simulated test. A consequence of undamaged and bruise damage is that it gives an increase of ion leakage in undamaged and bruised strawberries of the summer production, which was approximately twice as likely as with the winter production. Preharvest treatment is an alternative application by a calcium treatment to improve strawberry texture. For example, a calcium treatment along with boron may help give better strawberry quality and could be a future area of study. The application of calcium sulphate had no effect on firmness or calcium in 'Aromas' and 'Selva' strawberries (Naradisorn, 2008; Dunn and Able, 2006), while the pre-harvest foliar application of combination of calcium and boron could improve firmness and reduce disease (Singh *et al.*, 2007). Therefore, the pre-harvest application of calcium and boron may reduce the bruising incidence of summer strawberries, particularly 'Sonata' cultivar.

Given lesser TSS and higher TA content, the strawberries in the summer cultivation also had a less desirable flavour than the winter cultivation. However, the TSS content of strawberries from the summer cultivation was acceptable, with over 7 %TSS (Chapters 4 and 5). A difficulty with summer production is that long spells of hot weathers give smaller fruits, higher susceptibility to mechanical damage and fruits with a less acceptable flavour.

7.2.2 Strawberry cultivar influencing strawberry bruise and quality

The selection of strawberry cultivars should be concerned not only with taste and yield, but also with the shelf-life and ability to withstand the supply chain system (Terry *et al.*, 2011). 'Elsanta' and 'Sonata' cultivars (a June-bearing cultivar) are the most widely available strawberry cultivars in the UK market and can supply the UK market for about 8 months (Fresh produce Journal, 2012). However, most studies of strawberry's production and postharvest quality have only focussed on 'Elsanta' cultivar while few research studies in these fields have investigated the

‘Sonata’ cultivar. Commercial information reported that ‘Sonata’ fruits were more sensitive to higher temperature than ‘Elsanta’ fruits during growth and development, which led to less firmness (RW Walpole, 2014). Until recently, there has been no reliable research that proves more susceptibilty to bruising in ‘Sonata’ cultivar under growing at higher temperature.

The second research hypothesis of this study that there will be no difference in impact and vibration damages between ‘Elsanta’ and ‘Sonata’ cultivars (section 1.4, b). In the summer cultivation, ‘Sonata’ fruits had a higher susceptibility to bruise damage and a higher EC value than ‘Elsanta’ fruits after vibration test, but not impact test (sections 5.5.1.1 and 5.5.2.1). Thus, this hypothesis was correct for impact test but was not proved for vibration test. However, the overall physical fruit shape of ‘Sonata’ was not different from ‘Elsanta’ fruits, and fruit firmness between two cultivars was not consistent. Also, the fruits in vibration test were harvested after the peak of production throughout late season; thus this may increase the bruise damage of strawberries in vibration test, particularly ‘Sonata’ cultivar. This probability is supported by Terry *et al.* (2011), who reported late season harvesting of ‘Sonata’ fruits causes more fruit losses due to excessive softness. Also, RW Walpole (2014) stated that ‘Sonata’ cultivar is more susceptible to bruising and ripening than ‘Elsanta’ cultivar, particularly in hot weather. In the current study, ‘Elsanta’ cultivar had a consistent quality throughout the whole season due to resistance to bruise damage with good flavour. Thus, ‘Elsanta’ cultivar has been used to represent a good performance quality for the commercial strawberry in the postharvest handling and transport.

7.2.3 The simulated impact tests relate to the possibility of strawberry damage from practical handling

The procedure of strawberry handling and transport in the UK commonly has fewer steps than the strawberry handling in the US; for example, the commercial strawberry handling in the UK does not have an active modified atmosphere with plastic pallet cover (Mitcham, 2002). Also, most cooling facilities of the British strawberries offer room cooling, which uses a longer period for produce cooling than forced-air cooling, the US practice.

The hypotheses tested main research questions: 1) An increased drop height will give an increase in impact bruise for ‘Elsanta'’and ‘Sonata’ cultivars from the winter and summer cultivations after cool storage. 2) The increases in frequency and exposure time of vibration force will give more bruising after cool storage for both cultivars (section 1.4, c-e). (In the simulated vibration test, the hypothesis of vibration frequency will be explained and proved in the next section (section 7.2.4)).

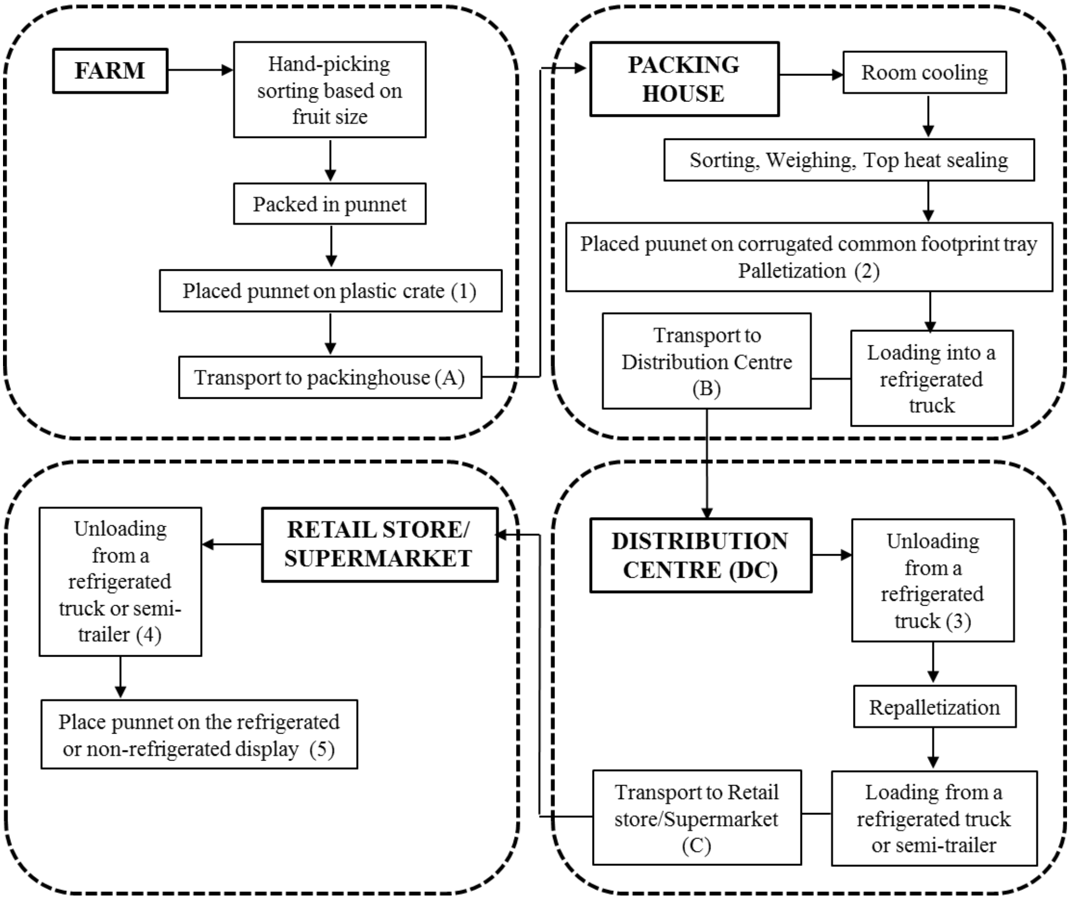


Figure 7.2: The strawberry journey from farm to retail store or supermarket in the UK. The letter and number mean the possibility of impact and vibration events, respectively. *Source*: Chaiwong (2015).

As shown in Figure 7.2, the principle handling steps for strawberries in the UK. It should be noted that the number and letter mean the possibility of impact damage from the 5 steps, and of vibration damage from the 3 steps, respectively. Commercially, the first step of strawberry handling starts hand-picking by either snap-picked or finger-picked. The snap-picking with a little stalk causes a higher mechanical damage from harvesting than that finger-picking. In the current study, the strawberries were harvested by the finger-picked method to avoid mechanical damage before starting simulated impact and vibration tests. The punnet was dropped 5 times from the heights from 250 to 1000 mm. The drop test was onto a steel sheet and the cool storage was for 3 days, the impact results of the current study showed that the maximum height limit of 500-750 mm gave an acceptable severity score over 3 levels.

The period of time for postharvest handling system for the simulated impact and vibration tests was a whole period of around 12 hr, which started from harvesting, and then onto cooling, weighing, packing and simulation test (11-12 hr) and shelf-life time (3 days). The lead time of an actual strawberry was 12-24 hr and typically shelf-life was 3 days (Terry *et al*., 2011). Furthermore, the previous studies of strawberry handling indicate the importance of the cooling method. A short delay of 4 to 8 hours from forced-air cooling directly affected quality characteristics of strawberries after storage or transport such as firmness, colour, decay and visual quality (Nunes *et al.*, 1995; Nunes *et al.*, 1995a; Pelletier *et al.*, 2011). In the current study, there was no delay in room cooling over an hour and the final cooling temperature reached to 7±1^{o}C, and therefore less effect on a delay cooling was observed in the quality changes. As a display in store or supermarket, the average air temperature of refrigerated and non-refrigerated displayed was 17^{o}C in the summer-autumn period (Chaiwong and Bishop, 2015). Moreover, the angle of the display shelf may be considered due to probably a reduced bruise level of strawberries from compression damage. Ferreira *et al.* (2009) found that a lesser angle of pendulum impactor at 45^{o} reduced bruise volume of ‘Chandler’cultivar at a full red stage when compared with its larger angle at 90^{o}. As expected, the results from actual handling often have a higher bruise damage level than the simulated tests in the laboratory due to finger-picking, high lead time, less careful handling in each step, more steps of operation and higher air temperature at the display.

7.2.4 The vibration level and temperature of the actual transport on the UK roads may affect strawberry bruise and quality

As stated previously the hypothesis in the actual transport study (section 6.1, a), it is expected that the refrigerated vehicle and travelling route will give a difference to the vibration and temperature levels and this has been shown to be a valid hypothesis. The results showed that the overall peak frequency of power density (PD) spectrum was found at 7 Hz (semi-trailer), 10 Hz (truck) in the 5-10 Hz spectrum. In the spectrum of 11-25 Hz, the results found to be 11-14 Hz (both vehicles) and 19 Hz for the upper deck of semi-trailer) (section 6.4.4). As a single drop delivery, the semi-trailer speed of approximate 70 km/hr on highways gave a higher g_{rms} value than for the truck speed on city roads at 20-45 km/hr due to a larger size and a higher speed.

Analysis was carried out by integrating frequency and acceleration levels from the simulated vibration and actual transport. The overall acceleration level was approximately 0.5 to 0.7 *g* and was over 1 *g* for less than 10% for the total acceleration level (section 6.4.2), which indicated the same range as for the simulated acceleration of 0.4 to 1.1 *g* from 3-5 Hz. However, the simulated conditions had maximum damage at the maximum frequency, which was 5 Hz. In practice higher frequencies occurred, so there may be higher damage (sections 5.5.1.1 and 5.5.2.1). Moreover, the travelling time on the London and Manchester routes was around an hour (3600 sec) or 3.5 hours (126000 sec) respectively, as opposed to the simulation time of 150 sec. Thus, there is a high possibility that the actual transport could cause an increase of bruised strawberries due to a higher frequency /acceleration and a longer travelling time, particularly in a refrigerated semi-trailer shipment.

Most of the actual transport studies for vibration level were reported and analysed using PSD plots, including shock level with high peaks (Lu *et al.*, 2010a). The shock clearly occurred for various road conditions such as road roughness, pedestrian crossing, road curve, left and right turn; therefore, the recommended vibration level analysis should have shock value removed (Lu *et al.*, 2008). For example, in the vibration analysis in truck transport in Japan is acceleration peak (*g*) of shock above 0.1 *g* (Lu *et al*., 2010a) or 0.7 *g* is removed (Lu *et al*., 2010c). The shock and vibration during the Japanese transport was found in the speed at 45-59.9 m/hr and slightly lower at a higher speed (Lu *et al*., 2010a), but it must be remembered that this is effectively a vibration study. In the current study, particularly, the lower speed of truck on the London routes (city streets) was round 20-30 km/hr (section 6.4.1); therefore it is possible for these to be included in the shock and vibration levels.

As regards the hypothesis in the actual transport study (section 6.1, c), the multidrop deliveries with partially loaded vehicles will give higher vibration levels for the same location than the fully loaded single drop delivery. The result showed that the vibration levels for the multidrop deliveries slightly increased after the first drop, particularly at a lower speed on city streets. Moreover, the hypotheses of this actual study is expected that the location of the consignment in the refrigerated vehicle will make a difference to the vibration level experienced. Also, it is expected that the temperature will remain uniform (± 1^{o}C) during shipment in refrigerated vehicles in city and long distance deliveries (section 1.4, g and h). Regarding a set point at 3^{o}C on both refrigerated vehicles, the overall range of temperature during food transport on city and highway roads were found in 2 to 8^{o}C, which showed a higher temperature than the set point temperature of 5^{o}C. Interestingly, with a mixed load with different package types on the same pallet the vibration levels of different position in the vehicle were still in agreement with previous studies for a full load of a single pallet type. The position in the vehicle and in the pallet needs to be particularly borne in mind with placing berry fruits in a mixed load. The front-bottom position with less vibration level was recommended for strawberries and other berry fruits with high susceptibility to bruising damage (section 6.4.3), and they also require a cooler temperature of around 5°C during transport, particularly in a semi-trailer on highways (section 6.4.5).

During the postharvest handling operation and transport of strawberries, therefore, the aspects to minimizing impact and vibration damages result in an increase in quality and a reduction of losses. To achieve this goal, it is suggested to reduce the number of handling steps or lead times from farm to retail store/supermarket, reduce the drop height, consider the pallet position in the vehicle, control the vehicle speed and reduce fluctuating temperature.

7.2.5 Assessment of bruise damage

Several attempts have been made to give bruising assessment of fruits, for example, bruise volume, fruit firmness and respiration rate, as well as visual assessment with a severity score of bruise area. So far, however, there has been little discussion about the EC method to evaluate bruised fruits for different levels of damage severity, especially for bruised strawberries. The final hypothesis is expected that a non-destructive method of bruise assessment will be developed as the rapid and accurate methods (section 1.4, f). Regarding the selected objective methods, the EC method gave a constant result with a significantly stronger correlation with wet bruise and a severity score after impact and vibration tests as compared with the respiration rate measurement, puncture and compression tests. Also, the puncture test with a probe of 8 mm had a greater correlation than the compression test with a platen of 42 mm (sections 4.5.4 and 5.5.3). These results from the EC and puncture tests show that for bruise assessment methods, there may be a high potential to develop this further. In the case of puncture test, this takes around 40 sec for each fruit, using a fruit texture analyser, and the results from the study indicate a minimum of 3 fruit is necessary to give an indication severity for each firmness method (120 sec). These fruits can be of varied weights, and no size grading is required in the current study. However, for commercial practice, this cannot be carried out on each individual sample. The use of firmness might give inconsistent result due to possibly the water status of the organ or pulp temperature (Miller, 1992), whilst the respiration rate also requires a long period for a whole punnet (7200

Sec), and could only distinguish bruised strawberries without giving the intensity level. In terms of chemical analysis, the TSS and TA analysis could not be used as an indicator of bruised strawberries (Chapters 4 and 5). After both impact and vibration tests, EC values on the initial day showed a significantly strong correlation with the bruise damages after storage for 3 days (sections 4.5.4.3 and 5.5.3.3). For the determination of either softer fruit or bruise fruit, the EC technique is suggested to be used as a bruise indicator as well as a bruise predictor for the rapid and accurate methods.

7.3 FUTURE RESEARCH

7.3.1 Application EC method for bruise assessment

A significant correlation between wet bruise and EC value from both impact and vibration tests was observed. There is a need to focus more bruise assessment methods. The EC method gave the possibility assessing the damage level of the whole punnet. This study has only looked at the EC results for individual fruit and has found that 600 sec an adequate produce results. The fruit size has not altered the results. Again the size of the fruit was not a factor. However, in this case it could be potentially interesting to look at whole punnet EC results, so that a whole punnet of strawberry fruits or other soft fruits is immersed in distilled water at a controlled temperature of 25^{o}C and a reading obtained. The temperature bath needs to be large enough to take the initial shock. Loading temperatures are cooler than 25^{o}C, which will warm up strawberries very fast in the temperature bath. Further work is needed on the speed of temperature adjustment and the overall EC figures. However, this method has potential to be used as a quick severity assessment of commercial loads.

7.3.2 Compression force, fruit-to-fruit impact and puncture damage

The punnet size of the British strawberry on market is commonly 400 g per pack for the summer season. Terry *et al.* (2011) reported that the requirements of price or promotion gave alternate punnet size. The punnet should be selected to give the correct size for packing due to restriction of fruit movement and to avoid fruit-to-fruit damage as vibration damage. Currently, it would appear that a larger punnet size has been often only a change in the punnet height with the same width and length; therefore, the impact force by fruit-to-fruit and an increase in compression time may also cause a rise of bruise damage in strawberries. After handling and storage, the fruit-to-fruit impact force may involve mechanical damage, particularly during storage after either vibration or impact damage. It is possible that the compression force could occur after packing, transport and putting on display like a static loading. This possibility is supported by Ferreira *et al*. (2008), who found that the bruise volume of strawberries from compression force was higher than impact force, indicating from the possibility of handling and grading in a packaging line.

Also, the bottom layer (fruit) of the package had particularly the maximum damage of strawberries (Aliasgarian *et al.*, 2013). The type of cushion sheet in the bottom of a punnet may reduce a minor force level from vibration and fruit-to-fruit impact. Moreover, there has been little discussed about puncture wounds from fruit movement (vibration force) and puncture force. This damage may occur with the stem of harvested fruits by finger-picking perforating the neighbouring fruits to cause puncture wounds, which lead to an increase of susceptibility to disease and a reduction of shelf-life (Li and Thomas, 2014). Therefore, there would be a need further study on compression, fruit-to-fruit impact, and puncture damage onto the strawberries.

7.3.3 Shock level and vibration on upper deck floor

In the current study, the high peaks of acceleration occurred in the strong vibration condition during the transport, and thus it should be included shock level. The further work on vibration analysis is required to exclude shock level. It should be done to investigate the shock and vibration in truck transport in the UK due to there being no research in this study. Given the higher acceleration and frequency levels on the upper deck floor at the middle position in a semi-trailer, there also has been no published research on the vibration level at this position. The tendency of results suggests that the front and rear positions on the upper deck should be expected to show the lowest and highest vibrations levels, respectively, like those positions on the lower deck floor in a semi-trailer or a truck. It would be of considerable value to answer which position gives high vibration level and frequency during the UK transport.

7.4 CONCLUSION

The studies of the British strawberry bruise and actual transport on the UK roads have been analysed and confirmed to manipulate preharvest and postharvest factors for a reduced susceptibility to mechanical damage of strawberries, especially impact and vibration damages. An early growing summer season is suggested to avoid a higher temperature period, which causes a number of smaller fruits, higher susceptibility to bruise damage and undesirable flavour fruits. In the simulated tests, a higher height of impact tests were negatively related to strawberry bruise, firmness, EC value and respiration rate as well as higher frequency and exposure time. As the developing method for bruise assessment, the EC method was a good indicator and a predictor for wet bruise incidence from all mechanical damages and it is suggested as a method to evaluate whole punnet and other soft fruits.

In packing house and distribution centre operations, the palletization in the vehicle should be particularly considered for the rear-top position or upper deck floor to reduce vibration damage for fresh fruits and vegetables which are either susceptible to mechanical damage or expensive products. Furthermore, the middle position of a truck or the front position of a semi-trailer needs to be allocated for produce liable to non-sensitive chilling injury. There should be a lower speed of the vehicle during food transport on the city streets in the rush hour, as well as for a semi-trailer with a higher speed over 70 km/hr on highways. Therefore, the reduction of bruise damage of strawberries is a great challenge due to high sensitivity to mechanical damage. Understanding the important factors may implement strategies to reduce bruising from farm to retail store or supermarket.

7.5 SUMMARY OF VALIDITY OF HYPOTHESES

Hypothesis	Validity
a) There will be a higher level of impact and vibration damages on summer cultivation crops of 'Elsanta' and 'Sonata' cultivars (section 1.4, a)	*Valid* The summer cultivation increased susceptibility to both damage types a in both cultivars evaluated as compared to that of the winter cultivation.
b) There will be no difference in impact and vibration damages between 'Elsanta' and 'Sonata' cultivars (section 1.4, b)	*Valid for impact damage, but invalid for vibration damage in the summer cultivation* In the summer cultivation, Sonata fruits have a greater vibration damage and a higher ion leakage than Elsanta fruits.
c) An increase drop height will give an increase in impact bruise for 'Elsanta''and 'Sonata' cultivars from the winter and summer cultivations after cool storage (section 1.4, c).	*Valid* Immediately the simulated impact test, the maximum height limit of 750 mm gave an acceptable severity score over 3 levels in both cultivars. After cool storage, the impact damage gradually increased to the highest height limit of 500 mm.
d) An increase in frequency/exposure time will give more bruising after cool storage for both cultivars (section 1.4, d and e).	*Valid* There were the three frequencies (3, 4 and 5 Hz) and three exposure times (50, 100 and 150 sec) plus control. The simulated vibration at the frequency of 5 Hz (1.1 *g*) for 150 sec gave a significantly higher vibration bruise than other treatments.
e) A non-destructive method of bruise assessment will be developed as the rapid and accurate methods (section 1.4, f).	*Valid* The EC method is suggested to be a potentially more useful technique as a bruise detector and a bruise predictor within 12 minutes when compared with puncture, compression and respiration rate measurements.

Hypothesis	Validity
f) In the actual transport of food shipments, the refrigerated vehicle and travelling route will give a difference to the vibration and temperature levels (section 1.6, a).	*Valid* For a single drop delivery, the semi-trailer with a higher speed on highways gave more vibration level than the refrigerated truck with a lower speed on urban roads.
g) It is expected that the location of the consignment in the refrigerated vehicle will make a difference to the vibration level experienced (section 1.6, b).	*Valid in case A (front-middle-rear) and C (top-bottom), but invalid in case B (right-left)* For the mixed load of different positions in the refrigerated vehicle, the front position gave less vibration level as compared to either middle or rear position, particularly at the lower vibration level in bottom position. The vibration level of right-left position was inconsistent.
h) The multidrop deliveries with partially loaded vehicles will give higher vibration levels for the same location than the fully loaded single drop delivery (section 1.6, c).	*Valid* The vibration levels for multidrop deliveries slightly increased after the first drop.
i) The temperature will remain uniform (± 1^{o}C) during shipment in refrigerated vehicles in city and on the long distance deliveries (section 1.6, d).	*Invalid* The overall range of temperature during food shipments in the short and long travelling was found to be 2 to 8^{o}C as regards a set point at 3^{o}C.

REFERENCES

Acıcan, T., AlibaŞ, K. and Özelkök, I. S. (2007) 'Mechanical damage to apples during transport in wooden crates', *Biosystems Engineering*, **96**, (2), 239-248.

Ahmadi, E. (2012) 'Bruise susceptibilities of kiwifruits as affected by impact and fruit properties', *Research in Agricultural Engineering*, **58**, (3), 107-113.

Ahmadi, E., Ghassemzadeh, H. R., Sadeghi, M. and Moghaddam, M. (2010) 'The effect of impact and fruit properties on the bruising of peach', *Journal of Food Engineering*, **97**, 110-117.

Ahmed, D. M., Yousef, A. R. M. and Hassan, H. S. A. (2010) 'Relationship between electrical conductivity, softening and colour of Fuerte avocado fruits during ripening', *Agriculture and Biology, Journal of North America*, **1**, (5), 878-885.

Alayunt, F. N., Çakmak, B., Can, H. Z. and Aksoy, U. (1998) 'Vibration damage trial on some fig cultivars', *Acta Horticulturae*, **480**, 305-310.

Ali, A., Abrar, M., Sultan, M. T., Din, A. and Niaz, B. (2011) 'Post-harvest physicochemical changes in full ripe strawberries during cold storage', *The Journal of Animal and Plant Science*, **21**, (1), 38-41.

Aliasgarian, S., Ghassemzadeh, H. R., Moghaddam, M. and Ghaffari, H. (2013) 'Mechanical damage of strawberry during harvest and postharvest operations', *World Applied Sciences Journal*, **22**, (7), 969-974.

Anderson, B. A., Sarkar, A., Thompson, J. F. and Singh, R. P. (2004) 'Commercial-scale forced-air-cooling-of packaged strawberries', *American Society of Agricultural Engineers*, **47**, 183-190.

AOAC. (1990) *Official methods of analysis of the Association of Official Analytical Chemists*, 2 vols (15th edition). Virginia: Association of Official Analytical Chemists.

Ashby, B. H. (2008) *Protecting perishable foods during transport by truck* [www.document]. http://www.convoyservicing.com/wp-content/uploads/2012/02/USDA-Handbook-Protectin-Perishable-Foods-During-Transport-by-Truck.pdf (Accessed 1 May 2015).

Atta-Aly, M. A., Ezzat, M. A. and Lasheene, Z. E. S. (1999) 'Reducing quality loss of strawberries during local marketing and exportation by using different cool chains', in Gerasopoulos D. (ed.), *Postharvest losses of perishable horticultural products in the Mediterranean region.* Chania: CIHEAM, 35-47.

Aung, M. M. and Chang, Y. S. (2014) 'Temperature management for the quality assurance of a perishable food supply chain', *Food Control,* **40**, 198-207.

Ayala-Zavala, J. F., Wang, S. Y., Wang, C. Y. and Gonzalez-Aguilar, G. A. (2004) 'Effect of storage temperatures on antioxidant capacity and aroma compounds in strawberry fruit', *Lebensmittel-Wissenschaft und-Technologie*, **37**, 687–695**.**

Azodanlou, R., Darbellay, C., Luisier, J. L., Villettaz, J. C. and Amadò, R. (2004) 'Changes in flavour and texture during the ripening of strawberries', *European Food Research and Technology*, **218**, 167-172.

Azodanlou, R., Darbellay, C., Luisier, J. L., Villettaz, J. C. and Amado, R. (2003) 'Quality assessment of strawberries (*Fragaria* Species)', *Journal of Agricultural and Food Chemistry,* **51,** 715-721.

Baldwin, E. A. (2014) *Flavor* [www.document]. http://www.ba.ars.usda.gov/hb66/flavor.pdf (Accessed 10 March 2015).

Barchi, G. L., Berardinelli, A., Guarnieri, L., Ragni, C. and Fila, C. T. (2002) 'Damage to loquats by vibration-simulating intra-state transport', *Biosystems Engineering,* **83**, (3), 305-312.

Bello, K., Idah, P. A. and Fadeyibi, A. (2013) ‘Damage of damage of tomatoes in Traditional palm baskets of different shape subjected to force vibration’, *Swiss Journal of Applied Sciences*, **2**, (8), 1-8.

Ben-Tzur, I. and Ward, G. (2009) ‘System approach to reducing waste in the fresh produce supply chain’, *Acta Horticulturae*, **880**, 125-136.

Berardinelli, A., Donati, V., Giunchi, A., Guarnieri, A. and Ragni, L. (2005) ‘Damage to pears caused by simulated transport’, *Journal of Food Engineering*, **66**, 219-226.

Bishop, C. F. H., Gash, A. F. J., Heslim, C. and Hanney, S. (2012) ‘The coefficient of friction of individual potatoes and various handling materials - Short communication’, *Research in Agricultural Engineering*, **58**, (3), 114-117.

Blahovec, J. and Papršrein, F. (2005) ‘Susceptibility of pear varieties to bruising’, *Postharvest Biology and Technology*, **38**, 231-238.

Boyette, M. D., Sanders, D. C., and Rutledge, G. A. (1996) *Packaging Requirements for Fresh Fruits and Vegetables* [www.document]. http://www.bae.ncsu.edu/programs/extension/publicat/postharv/ag-414-8/ (Accessed 1 March 2015).

British Summer Fruits (2012) *Strawberry* [www.document]. http://www.britishsummerfruits.co.uk/html/strawberries.htm (Accessed 13 August 2015).

Brusewitz, G. H. and Bartsch, J. A. (1989) ‘Impact parameters related to post harvest bruising of apples’ *Transactions of the ASAE (American Society of Agriculture Engineers)*, **32**, (3), 953-957.

Burton, C. L. and Schulte-Pason, N. L. (1987) ‘Carbon dioxide as an indicator of fruit impact damage’, *HortScience*, **22**, (2), 281-282.

Bugaud, C., Ocrisse, G., Salmon, F. and Rinalso, D. (2014) 'Bruise susceptibility of banana peel in relation to genotype and post-climacteric storage conditions' *Postharvest Biology and Technology,* **87**, 113-119.

Çakmak, B., Alayunt, F. N., Akdeniz, R. C., Aksoy, U. and Can, H. Z. (2010) 'Assessment of the quality losses of fresh fig fruits during transport', *Journal of Agricultural Sciences,* **16**, 183-193.

California Strawberry Commission (2006) *Best handling practices for fresh strawberries* [www.document]. http://www.calstrawberry.com/fileData/docs/Best_Handling_Practices_For_Fresh_Strawberries.pdf (Accessed 3 April 2013).

Calleja, E. J., Ilbery, B. and Mills, P. R. (2012) 'Agricultural change and the rise of the British strawberry industry, 1920–2009', *Journal of Rural Studies*, **28**, (4), 603-611.

Caner, C., Aday, M. and Demir, M. (2008) 'Extending the quality of fresh strawberries by equilibrium modified atmosphere packaging', *European Food Research and Technology,* **227**, (6), 1575-1583.

Cantwell, M. I. and Kasmire, R. E. (2002) 'Postharvest Handling Systems: Underground Vegetables (Roots, Tubers, and Bulbs', in A.A. Kader (ed.), *Postharvest Technology of Horticultural Crops* (3rd edition). California: University of California, Division of Agriculture and Natural Resources, 435-443.

Castro, I., Teixeira, J. A., Salengke, S., Sastry, S. K. and Vicente, A. A. (2004) 'Ohmic heating of strawberry products: electrical conductivity measurements and ascorbic acid degradation kinetics', *Innovative Food Science and Emerging Technologies,* **5**, 27–36.

Ceponis, M. J., Cappellini, R. A. and Lightner, G. W. (1987) 'Disorders in sweet cherry and strawberry shipments to the New York Market, 1972-1984', *Plant Disease,* **71**, (5), 472-475.

Chaiwong, S. and Bishop, C. F. H. (2015) 'Use of an insulated bag from the supermarket to maintain 'Elsanta' strawberry temperature to households', *Acta Horticulturae,* **1079**, 187-192.

Chen, P., Ruiz, M., Lu, F. and Kader, A. A. (1987) 'Study of impact and compression damage on Asian Pears', *Transactions of the ASAE (American Society of Agriculture Engineers),* **30** (4), 1193-1197.

Chonhenchob, V, Singh, S. P., Singh, J. J., Sittipod, S., Swasdee, D. and Pratheepthinthong, S. (2010) 'Measurement and analysis of truck and rail vibration levels in Thailand', *Packaging Technology and Science*, **23**, 91-100.

Chonhenchob, V., Chriyachotilert, S. and Singh, S. P. (2011) 'Packaging in fresh produce supply chains in Thailand' in A. A. S. Villahermosa, L. N. Bihn, R. S. Rolle and V. Chonhenchob. *Packaging in fresh produce supply chain in Southeast Asia*. Bangkok: Food and Agriculture Organization of the United Nations, RAP Publication 2011/20, 43-99.

Chonhenchob, V., Singh, S. P., Singh, J. J., Stallings, J. and Grawal, G. (2012) 'Measurement and analysis of vehicle vibration for delivering packages in small-sized and medium-sized trucks and automobiles', *Packaging Technology and Science,* **25**, 31-38.

Chonhenchob, V., Sittipod, S., Swasdee, P., Rachtanapun, S., Singh, S. P. and Singh, J. (2009) 'Effect of truck vibration during transport on damage to fresh produce shipments in Thailand', *Journal of Applied Packaging Research*, **3**, (1), 27-38.

Collins, J. K. and Perkins-Veazie, P. (1993) 'Postharvest changes in strawberry fruit stored under simulated retail display conditions', *Journal of Food Quality,* **16** (2),133-143.

Cordenunsi, B. R., Nascimento J. R. O., Genovese, M. I. and Lajolo, F. M. (2002) 'Influence of cultivar on quality parameters and chemical composition of strawberry fruits grown in Brazil', *Journal of Agricultural and Food Chemistry,* **50**, 2581-2586.

Cordenunsi, B. R., Nascimento, J. R. O. and Lajolo, F. M. (2003) 'Physico-chemical changes related to quality of five strawberry fruit cultivars during cool-storage', *Food Chemistry*, **83**, 167-173.

Cordenunsi, B. S., Genovese, M. I., Do-Nascimento, J. R. D., Aymoto-Hassimotto, N. M., Santos, R. J. D. and Lajolo, F. M. (2005) 'Effects of temperature on the chemical composition and antioxidant activity of three strawberry cultivars', *Food Chemistry,* **91**, 113-121.

Corrugated Packaging Alliance (2003) *Corrugated Packaging for Produce* [www.document]. http://www.fibrebox.org/upload/CommonFootprint_
MarketingBrochure-1-REV509.pdf (Accessed 1 March 2015).

Crisosto, C. H. and Mitchell, J. P. (2002) Preharvest Factors Affecting Fruit and Vegetable Quality in A. A. Kader (ed.), *Postharvest Technology of Horticultural Crops* (3rd edition). Oakland: University of California, Division of Agriculture and Natural Resources, 49-54.

Defra Food and Farming Group (2011) *Attitudes and Behaviours around Sustainable Food Purchasing*. London: SERP 1011/10.

Deng, Y., Wu, Y. and Li, Y. (2005) 'Effects of high O_2 levels on post-harvest quality and shelf life of table grapes during long-term storage', *European Food Research and Technology,* **221**, 392-397.

Department for Environment Food and Rural Affairs (2012) *Food transport indicators to 2010* [www.document].
https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/138104/defra-stats-foodfarm-food-transport-statsnotice-120110.pdf (Accessed 1 May 2015).

Department for Environment Food and Rural Affairs (2014) *Basic Horticultural Statistics 2014* [www.document]. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/341921/hort-report-07aug14.pdf (Accessed 5 August 2015).

Department for Transport (2003) *Simplified guide to lorry types and weights* [www document]. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/211948/simplified-guide-to-lorry-types-and-weights.pdf (Accessed 1 March 2015).

Department of Energy and Climate Change (2015) *Transport energy consumption in the UK between 1970 and 2015*. [www.document]. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/395007/stats_summary_2015.pdf (Accessed 15 September 2015).

Desmet, M., Lammertyn, J., Scheerlinck, N., Verlinden, B. E. and Nocolaï, B. M. (2003) 'Determination of puncture injury susceptibility of tomatoes', *Postharvest Biology and Technology*, **27**, 293-303.

Don, E. (2015a) *Botrytis Rot (2)* [www.document]. http://postharvest.ucdavis.edu/PFfruits/StrawberryPhotos/?repository=29677&a=83692 (Accessed 20 April 2015).

Don, E. (2015b) *Abrasion damage* [www document]. http://postharvest.ucdavis.edu/PFfruits/StrawberryPhotos/?repository=29677&a=83689 (Accessed 15 March 2015).

Døving, A. and Måge, F. (2002) 'Methods for testing strawberry fruit firmness', *Acta Agriculturae Scandinavica*, **51**, (1), 43-51.

Døving, A., Måge, F. and Vestrheim, S. (2005) 'Methods for testing strawberry fruit firmness', *Small Fruits Review*, **4**, (2), 11-34.

Dunn, J. L. and Able, A. J. (2006) 'Pre-harvest calcium effects on sensory quality and calcium mobility in strawberry fruit', *Acta Horticulturae*, **708**, 307-312.

Eloisa, M., Quintana, G. and Paull, R. E. (1993) 'Mechanical injury during postharvest handling of 'Solo' papaya fruit', *Journal of the American Society for Horticultural Science*, **118**, (5), 618-622.

English Food and Farming Partnerships (EFFP) (2010) *Driving Change in the Fresh Produce Sector.* [www.document]. http://archive.defra.gov.uk/foodfarm/food/policy/partnership/fvtf/documents/effp-report.pdf (Accessed 20 April 2013).

Ferreira, M. D., Sargent, S. A., Brecht, J. K. and Chandler, C. K. (2008) 'Strawberry fruit resistance to simulated handling', *Scientia Agricola (Piracicaba, Braz.)*, **65**, (5), 490-495.

Ferreira, M. D., Sargent, S. A., Brecht, J. K. and Chandler, C. K. (2009) 'Strawberry bruising sensitivity depends on the type of force applied, cooling method, and pulp temperature', *HortScience*, **44**, (7), 1953-1956.

Fischer, D., Craig, W. L., Watada, A. E., Douglas, W. and Ashby, B. H. (1992) 'Simulated in-transit vibration damage to packaged fresh market grapes and strawberries', *Applied Engineering in Agriculture*, **8**, (3), 363-366.

Food and Agricultural Organisation of the United States (FAO) (2014) *Strawberry* [www.document]. http://faostat.fao.org/site/567/DesktopDefault.aspx?PageID=567#ancor (Accessed 13 August 2015).

Fredericks, C. H., Fanning, K. J., Gidley, M. J., Netzel, G., Zabaras, D., Herrington, M. and Netzel, M. (2012) 'High-anthocyanin strawberries through cultivar selection', *Journal of the Science of Food and Agriculture*, **94**, (3), 846-852.

Fresh Produce Journal (2012) Refresh directory 2012: an essential resource for the fresh produce industry. London.

García, J. L., Ruiz-Altisent, M. and Barreiro, P. (1995) 'Factors influencing mechanical properties and bruise susceptibility of apples and pears', *Journal of Agricultural Engineering Research*, **61**, 11-18.

Garcia-Romeu-Martinez, M. A., Singh, S. P. and Cloquell-Ballester, V. A. (2008) 'Measurement and analysis of vibration levels for truck transport in Spain as a function of payload, suspension and speed', *Packaging Technology and Science*, **21**, 439-451.

Giampieri F., Tulipani, S., Alvarez-Suarez, J. M., Quiles, J. L., Mezzetti, B. and Battino, M. (2012) 'The strawberry: Composition, nutritional quality, and impact on human health', *Nutrition*, **28**, 9-19.

Gołacki, K., Rowiński, P., Stropek, Z. (2009) 'The determination of apples bruise resistance by the multiple impact method', *Technical Sciences*, **12**, 29-39.

Gontard, N. and Guillaume, C. (2010) 'Packaging and Shelf Life of Fruits and Vegetables', in G. L. Robertson Food (ed.), *Food Packaging and Shelf-life.* Florida: CRC Press, 297-315.

Gustavsson, J., Cederberg, C., Sonesson, U., Otterdijk, R. V. and Meybeck, A. (2011) *Global food losses and food waste*. Rome: the Food and Agriculture Organization of the United Nations.

Hancock, J. F. (1999) *Strawberries*. Cambridge: the University Press.

Harvey, J. M., Harris C. M., Tietjen W. J. and Seriol, T. (1980) *Quality maintenance in truck shipments of Californian strawberries*. Washington: U.S. Department of Agriculture, AAT-W-12.

Hernanz, D., Recamales, A. F., Meléndez-Martínez, A. J., González-Miret, M. L. and Heredia, F. J. (2008) 'Multivariate statistical analysis of the color/anthocyanin relationships in different soilless-grown strawberry genotypes' *Journal of Agricultural and Food Chemistry,* **56**, 2735-2741.

Hietaranta, T. and Linna, M. M. (1999) 'Penetrometric measurement of strawberry fruit firmness: Device testing', *HortTechnology,* **85**, 1-5.

Hinsch, R. T., Slaughter, D. C., Craig, W. L. and Thompson, J. F. (1993) 'Vibration of fresh fruits and vegetables during refrigerated truck transport', *Transactions of the ASAE (American Society of Agriculture Engineers),* **36**, (4), 1039-1042.

HM Revenue and Customs (2013) *Moving goods by road* [www document]. https://www.gov.uk/moving-goods-by-road (Accessed 1 March 2015).

Ho, H. S. (2006) 'Republic of Korea (1)' in R. S. Rolle (ed). *Postharvest management of fruit and vegetables in the Asia-Pacific Region*. Tokyo: Asian Productivity Organization, 175-186.

Hodges, R. J., Buzby, J. C. and Bennett, B. (2010) 'Postharvest losses and waste in developed and less developed countries: opportunities to improve resource use', *The Journal of Agricultural Science,* **149**, 37-45.

Holcroft, D. M. and Kader, A. A. (1999) 'Controlled atmosphere-induced changes in pH and organic acid metabolism may affect color of stored strawberry fruit'. *Postharvest Biology and Technology*, **17**, 19–32.

Holt, J. E. and Schoorl, D. (1982) 'Strawberry bruising and energy dissipation', *Journal of Texture Studies*, **13**, 349-357.

Hui, K. P. C. (2001) *Air circulation inside refrigerated semi-trailers transporting fresh produce*. Unpublished MSc thesis. Montreal: McGrill University.

Hui, K. P. C., Raghavan, G. S. V., Vigneault, C. and de Castro, L. R. (2006) 'Evaluation of the air circulation uniformity inside refrigerated semi-trailer transporting fresh horticultural produce', *Journal of Food, Agriculture and Environment*, **4**, (1), 109-114.

Hung, Y.C. and Prussia, S.E. (1989) 'Effect of maturity and storage time on the bruise susceptibility of peaches (cv. Red Globe)', *Transactions of the ASAE (American Society of Agriculture Engineers)*, **32**, (4), 1377-1382.

Idah, P. A., Ajisegiri, E. S. A. and Yisa, M. G. (2007) 'An assessment of impact damage to fresh tomato fruits', *Assumption University Journal of Technology,* **10**, (4), 271-275.

Ishikawa, Y., Katazawa, H. and Shina, T. (2009) 'Vibration and shock analysis of fruit and vegetables transport - Cherry Transport from Yamagata to Taipei', *The Japan Agricultural Research Quarterly,* **43**, (2), 129-135.

Izumi, T., Toshihiro, T., Hatsuko, M., Massanobu, T., Yan, L. J.,Takayuki, K. and Hideaki, O. (1999) 'Effect of vibration by simulated transportation on respiration rate and quality of strawberry fruits', *Food Preservation Science,* **25**, (1), 15-20.

Jarimopas, B., Singh, S. P. and Saengnil, W. (2005) 'Measurement and analysis of truck transport vibration levels and damage to packaged tangerines during transit', *Packaging Technology and Science*, **18**, 179-188.

Jeong, M., An, D. S., Lee, S. J. and Lee, D. S. (2011) 'A master packaging system for preserving strawberries in the fresh produce supply chain', *Journal of Food, Agriculture and Environment,* **9**, 114-117.

Jiang, Y., Shina, T., Nakamura, N. and Nakahara, A. (2001) 'Electrical conductivity evaluation of postharvest strawberry damage', *Journal of Food Science,* **66**, (9), 1392-1395.

Jiménez-Jiménez, F., Castro-García, S., Blanco-Roldán, G. L., Ferguson, L., Rosa, U. A. and Gil-Ribes, J. A. (2013) 'Table olive cultivar susceptibility to impact bruising', *Postharvest Biology and Technology*, **86**, 100-106.

Joung, H. M. and Park, J. G. (2012) 'Effect of vibration stress on the quality of packaged apples during simulated transport', *Journal of Biosystems Engineering*, **37**, (1), 44-50.

Kader, A. A. (1991) 'Quality and its maintenance in relation to the postharvest physiology of strawberry', in A. Dale and J. J. Luby (ed.), *The Strawberry into the 21st*. Oregon: Timber Press, 145-152.

Kader, A. A. (1999) 'Fruit maturity, ripening, and quality relationships', *Acta Horticulturae*, **485**, 203-208.

Kader, A. A. (2002a) 'Postharvest Biology and Technology: An Overview', in A. A. Kader (ed.), *Postharvest Technology of Horticultural Crops* (3rd edition). Oakland: University of California, Division of Agriculture and Natural Resources, 39-47.

Kader, A. A. (2002b) 'Quality and Safety Factors: Definition and Evaluation of Fresh Horticultural Crops', in A.A. Kader (ed.), *Postharvest Technology of Horticultural Crops* (3rd edition). Oakland: University of California, Division of Agriculture and Natural Resources, 279-286.

Kader, A. A. (2002c) 'Standardization and Inspection of Fresh Fruits and Vegeables', in A.A. Kader (ed.), *Postharvest Technology of Horticultural Crops* (3rd edition). California: University of California, Division of Agriculture and Natural Resources, 287-300.

Kader, A. A. (2005) 'Increase food availability by reducing postharvest losses of fresh produce', *Acta Horticulturae*, **685**, 2169-2174.

Kader, A. A. (2013) *Banana* [www.document]. http://postharvest.ucdavis.edu/PFfruits/Banana/ (Accessed 5 August 2015).

Kader, A. A., Singh, R. P. and Mannapperuma, J. D. (1998) 'Technologies to extend the refrigerated shelf life of fresh fruits', in I. A. Taub, and R. P. Singh (ed.), *Food Storage Stability,* Florida: CRC Press, 419-434.

Kafkas, E., Koşar, M., Paydaş, S., Kafkas, S. and Başer, K. H. C. (2007) 'Quality characteristics of strawberry genotypes at different maturation stages', *Food Chemistry*, **100**, 1229–1236.

Kajuna, S. T. A. R., Bilanski, W. K. and Mittal, G. S. (1997) 'Response of bananas and plantains to impact forces', *Journal of Texture Studies,* **28**, 71-85.

Kalt, W., Forney, C. F., Martin A. and Prior, R. L. (1999) 'Antioxidant capacity, vitamin C, phenolics, and anthocyanins after fresh storage of small fruits', *Journal of Agricultural and Food Chemistry,* **47***,* 4638-4644.

Kalt, W., Prange, R. K. and Lidsterl, P. D. (1993) 'Postharvest color development of strawberries: Influence of maturity, temperature and light '*Canadian Journal of Plant Science,* **73**, 541-548.

Kartal, S., Aday, M. S. and Caner, C. (2012) 'Use of microperforated films and oxygen scavengers to maintain storage stability of fresh strawberries', *Postharvest Biology and Technology,* **71**, 32-40.

Kitazawa, H., Saito, K. and Ishikawa, Y. (2014) 'Effect of difference in acceleration and velocity change on product damage due to repetitive shock', *Packaging Technology and Science,* **27**, 221-230.

Kitthawee, U., Pathaveerat, S., Srirungruang, T. and Slaughter, D. (2011) 'Mechanical bruising of young coconut', *Biosystem Enginerring,* **109***,* 211-219.

Knee, M and Miller, A. R. (2002) 'Mechanical injury', in M. Knee (ed), Fruit quality and its biology basis. Sheffield: Sheffield Acadamic Press Ltd, 257-179.

Kojima, T., Lui, J. Y., Fujita, S., Inaba, S., Tanaka, M. and Tatara, I. (1999) 'Analysis of vibration and its effect on strawberries during highway transport', *Journal of the Society of Agricultural Structures, Japan*, **29** (4), 197-203.

Koyuncu, M. A. and Dilmaçünal, T. (2010) 'Determination of vitamin c and organic acid changes in strawberry by HPLC during cold storage', *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*, **38** (3), 95-98.

LeBlanc, D. I. and Hui, K. P. C. (2005) 'Land transportation of fresh fruits and vegetables: an update', *Stewart Postharvest Review*, **1** (4), 1-13.

Ledesma, N. A., Nakata, M. and Sugiyama, N. (2008) 'Effect of high temperature stress on the reproductive growth of strawberry cvs. 'Nyoho' and 'Toyonoka', *Scientia Horticulturae*, **116**, 186-193.

Lee, D. S., Yam, K. L. and Piergiovanni, L. (2008) *Food Packaging Science and Technology*. Florida: CRC Press.

Lee, E, Berry, A. D. and Sargent, S. A. (2004) 'Impact thresholds to maximize postharvest quality of Roma-type tomato', *Proceedings of the Florida State Horticultural Society*, 117, 373-377.

Lee, E., Sargent, S. A. and Huber, D. (2007) 'Physiological changes in Roma-type tomato induced by mechanical stress at several ripeness stages, *HortScience*, **42** (5), 1237-1242.

Lee, H. J., Kim, T. C., Kim, S. J. and Park, S. J. (2005) 'Bruising injury of persimmon (*Diospyros kaki* cv. Fuyu) fruits', *Scientia Horticulturae*, **103**, 179–185.

Lewis, R., Yoxall, A., Marshall, M. B. and Canty, L. A. (2008) 'Characterising pressure and bruising in apple fruit', *Wear*, **264**, 37-46.

Leyte, J. C. and Forney, C. F. (1999) ‘Optimizing flat design for forced-air cooling of blueberries packaged in plastic clamshells’, *HortTechnology*, **9**, 202-205.

Li, Z. and Thomas, C. (2014) ‘Quantitative evaluation of mechanical damage to fresh fruits’, *Trends in Food Science and Technology*, **35**, 138-150.

Lu, F., Ishikawa, Y., Kitazawa, H. and Satake, T. (2010a) ‘Effect of vehicle speed on shock and vibration levels in truck transport’, *Packaging Technology and Science*, **23**, 101-109.

Lu, F., Ishikawa, Y., Kitazawa, H. and Satake, T. (2010b) ‘Measurement of impact pressure and bruising of apple fruit using pressure-sensitive film technique’, *Journal of Food Engineering*, **96**, 614-620.

Lu, F., Ishikawa, Y., Kitazawa, H. and Satake, T. (2010c) ‘Effect of sampling parameters on shock and vibration level in truck transport’, in T. Goedecke (ed.) *Proceeding of the 17th IAPRI World Conference on Packaging,* Tianjin, China, 2-15 October 2010, Scientific Research Publishing Inc, 129-135.

Lu, F., Ishikawa, Y., Kitazawa, H. and Satake, T. (2012) ‘Assessment and prediction of repetitive impact damage to apple fruit using pressure-sensitive film technique’, *Journal of Food Agriculture and Environment*, **10**, (2), 156-160.

Lu, F., Ishikawa, Y., Shiina, T. and Sakate, T. (2008) ‘Analysis of shock and vibration in truck transport in Japan’, *Packaging Technology and Science*, **21**, 479-489.

Lui, J. Y. and Kojima, T. (1997) ‘Effect of vibration and storage temperatures on quality of strawberries’, *Journal of the Society of Agricultural Structures, Japan*, **8**, (3), 135-142.

MacLeod, R. F., Kader, A. A. and Morris, L. L. (1976) ‘Stimulation of ethylene and CO_2 production of mature green tomatoes by impact bruising’, *HortScience*, **11**, (6), 604-606.

Macnish, A. J., Padda, M. S., Pupin, F., Tsouvaltzis, P. I., Deltsidis, A. I., Sims, C. A., Brecht, J. K. and Mitcham, E. J. (2012) 'Comparison of pallet cover systems to maintain strawberry fruit quality during transport', *HortTechnology*, **22** (4), 493-501.

Mahmood, T., Anwar, F., Abbas, M. and Saari, N. (2012) 'Effect of maturity on phenolics (phenolic acids and flavonoids) profile of strawberry cultivars and mulberry species from Pakistan', *International Journal of Molecular Sciences*, **13**, 4591-4607.

Maness, N. O., Brusewitz, G. H. and McCollum, T. G. (1992) 'Impact bruise resistance comparison among peach cultivars', *HortScience*, **27**, (9), 1008-1011.

Mao, L., Ying, T., Xi, Y. and Zhen, Y. (1995) 'Respiration rate, ethylene production, and cellular leakage of fig fruit following vibrational stress', *HortScience*, **30**, (1), 145.

Marcondes, J. (2009) 'Vibration', in K. L. Yam (ed.), *The Wiley Encyclopedia of Packaging Technology* (3rd edition). New York: John Wiley & Sons Inc, 1266-1270.

Massey, L. M., Chase, B. R. and Starr, M. S. (1982) 'Effect of rough handling on CO_2 evolution or 'Hewes' cranberries', *HortScience*, **17**, (1), 57-58.

Mencarelli, F., Massantini, R. and Botondi, R. (1996) 'Influence of impact surface and temperature on the ripening response of kiwifruit', *Postharvest Biology and Technology*, **8**, 165-177.

Meulenbroek, E. J (2007) Strawberry Plant Named 'Sonata'. United States Plant Patent, US PP18,000 P2. 11 September 2007.

Milczarek, R. R., Saltviet, M. E., Gravey, C. and MaCarthy, M. J. (2009) Assessment of tomato pericarp mechanical damage using multivariate analysis of magnetic resonance images', *Postharvest Biology and Technology*, **52**, 189–195.

Miller, A. R. (1992) 'Physiology, biochemistry and detection of bruising (mechanical stress) in fruits and vegetables', *Postharvest News and Information*, **3**, (3), 53N-58N.

Mirzaee, M. and Bishop, C. F. H. (2010) ‘The packaging implications of the ‘last mile of the strawberry supply chain’, *Acta Horticulturae*, **877**, 967-972.

Mirzaee, M., Bishop, C. and Namit, S. (2008) ‘Implication of temperature changes during the strawberry supply chain’, *Journal of Agricultural Machinery Science*, **4**, (4), 318-387.

Mitcham, B. (1996) ‘Quality assurance for strawberry: A Case study’, *Perishables Handling Newsletter Issue,* **85**, 6-9.

Mitcham, B., Cantwell, M. and Kader, A. (1996) ‘Methods for determining quality of fresh commodities’, *Perishables Handling Newsletter Issue*, **85**, 1-5.

Mitcham, E. (2007) ‘Quality of berries associated with preharvest and postharvest conditions’, in Y. Zhao (ed.), *Berry Fruit Value-Added Products for Health Promotion*. Florida: CRC Press, 207-228.

Mitcham, E. J. (2014) *Strawberry* [www.document]. http://www.ba.ars.usda.gov/hb66/strawberry.pdf (Accessed 20 April 2015).

Mitcham, E. J. and Mitchell, F. G. (2002) ‘Strawberry and Cane Berries’, in A. A. Kader (ed.), *Postharvest Technology of Horticultural Crops* (3rd edition). Oakland: University of California, Division of Agriculture and Natural Resources, 364-370.

Mohsenin, N. N. (1986) ‘Physical properties of plant and animal materials: structure’, in: *Physical Characteristics and Mechanical Properties* (1st edition). Gordon and Breach Science Publishers Inc., New York.

Moing, A., Renaud, C., Gaudillère, M., Raymood, P., Roudeillac, P. and Denoyes-Rothan, B. (2001), ‘Biochemical changes during fruit development of four strawberry cultivars’, *Journal of the American* Society for *Horticultural Science*, **126**, (4), 394-403.

Montero, C. R. S., Schwarz, L. L., Santos, L. C., Andreazza, C. S., Kechinski, C. P. and Bender, R. J. (2009) ‘Postharvest mechanical damage affects fruit quality of ‘Montenegrina’ and ‘Rainha’ tangerines’, *Pesquisa Agropecuária Brasileira*, 44, (12), 1639-1640.

Montero, T. M., Mollà, E. M., Esteban, R. M. and López-Andréu F. J. (1996) ‘Quality attributes of strawberry during ripening’, *Scientia Horticulturae*, **65**, 239-250.

Moris, S. A. (2011) *Transportation, distribution and product damage*. West Sussex: John Wiley & Sons, Inc.

Nakamura, N., Inatsu, Y., Kawamoto, S., Okadome, H., Nakano, K., Maezawa, S. and Shina, T. (2007a) ‘Effect of vibration on the bacterial growth on strawberry fruits’, *Journal of Food, Agriculture and Environment*, **5**, (1), 44-48.

Nakamura, N., Umehara, H., Nei, D., Okadome, H., Ishikawa, Y., Nakano, K., Maezawa, S. and Shina, T. (2008) ‘Effect of package conditions on the damage of strawberries’, *Journal of the Society of Agricultural Structures, Japan*, **39**, (1), 1-8.

Nakamura, N., Umehara, H., Okadome, H., Nakano, K., Maezawa, S. and Shina, T. (2007b) ‘Effect of vibration frequency and direction on damage of strawberries’, *Journal of the Society of Agricultural Structures, Japan*, 3**8**, (2), 101-108.

Nakamura, R., Inaba, A., Ito, T. and Imanaga, T. (1986) ‘Changes in organic acid contents of tomato and japanese pear fruits during and after vibration’ *Journal of the Society of Agricultural Structures, Japan*, **55**, (1), 93-103.

Naradisorn, M. (2008) *Effect of nutrition on postharvest quality and grey mould development in strawberries*. Umpubished PhD thesis. Adelaide: The University of Adelaide.

NSW Agriculture (2004) *Strawberry disease control guide* [www.document]. http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0011/119558/strawberry-disease-control.pdf (Accessed 20 April 2013).

Nunes, C. N. and Emond, J. P. (2007) 'Relationship between weight loss and visual quality of fruits and vegetable' *Proceedings of the Florida State Horticultural Society*, **120**, 235-245.

Nunes, M. C. N, Brecht, J. K., Morais, A. M. M. B. and Sargent, S. A. (2006) 'Physico-chemical changes during strawberry development in the field compared with those that occur in harvested fruit during storage', *Journal* of the *Science* of *Food* and *Agriculture*, **86**, 180-190.

Nunes, M. C. N., Brecht, J. K., Morais, A. M. M. B. and Sargent, S. A. (1998) 'Controlling temperature and water loss to maintain ascorbic acid levels in strawberries during postharvest handling', *Journal of Food Science,* **63** (6), 1033-1036.

Nunes, M. C. N., Brecht, J. K., Morais, A. M. M. B. and Sargent, S. A. (2005a) 'Possible influences of water loss and polyphenol oxidase activity on anthocyanin content and discoloration in fresh ripe strawberry (cv. Oso Grande) during storage at 1^{o}C', *Journal of Food Science*, **70**, (1), S79-S84.

Nunes, M. C. N., Brecht, J. K., SArgent, S. A. and Morais, A. M. M. B. (1995) 'Effects of delays to cooling and wrapping on strawberry quality (cv. Sweet Charlie)', *Food Control,* 6, 323-328.

Nunes, M. C. N., Emond, J. P. and Brecht J. K. (2003) 'Quality of strawberries as affected by temperature abuse during ground, in-flight and retail handling operations', *Acta Horticulturae,* **604**, 239–246.

Nunes, M. C. N., Emond, J. P., Rauth, M., Dea, S. and Chau, K. V. (2009) 'Environmental conditions encountered during typical consumer retail display affect fruit and vegetable quality and waste', *Postharvest Biology and Technology*, **51**, 232-241.

Nunes, M. C. N., Morais, A. M. M. B., Brecht, J. K., Sargent, S. A. and Bartz, J. A. (2005b) 'Prompt cooling reduces incidence and severity of decay caused by *Botrytis cinerea* and *Rhizopus stolonifer* in strawberry', *HortTechnology*, **15**, (1), 153-156.

Opara, U. L. and Pathare, P. B. (2014) 'Bruise damage measurement and analysis of fresh horticultural produce - A review', *Postharvest Biology and Technology*, **91**, 9-24.

Organisation for Economic Co-Operation and Development (OECD) (2005) *International Standardisation of Fruit and Vegetables, Strawberries* [www document] http://www.oecd.org/tad/code/46597780.pdf (Accessed 27 April 2015).

Ornelas-Paz, Jde. J., Yahia E. M., Ramírez-Bustamante, N., Pérez-Martínez, J. D., Escalante-Minakata, Mdel. P., Ibarra-Junquera, V., Acosta-Muñiz, C., Guerrero-Prieto, V. and Ochoa-Reyes, V. (2013) 'Physical attributes and chemical composition of organic strawberry fruit (*Fragaria* x *ananassa* Duch, Cv. Albion) at six stages of ripening', *Food Chemistry*, **138**, 372-381.

Palencia, P., Martínez, F., Medina J. J. and Medina, J. L. (2013) 'Strawberry yield efficiency and its correlation with temperature and solar radiation', *Horticultura Brasileira*, **31**, 93-99.

Pang, W., Studman, J. and Ward, G. T. (1992) 'Bruising damage in apple-to-apple impact', *Journal of Agricultural Engineering Research*, **52**, 229-240.

Pelletier, W., Brecht, J. K., Nunes, M. C. N. and Émond, J. P. (2011) 'Quality of strawberries shipped by truck from California to Florida as influenced by postharvest temperature management practices', *HortTechnology*, **21** (4): 482-493.

Ṕeneau, S., Brockhoff, P. B., Escher, F. and Nuessli J. (2007) 'A comprehensive approach to evaluate the freshness of strawberries and carrots', *Postharvest Biology and Technology*, **45**, 20-29.

Perkins Veazie P. 1995. *Growth and ripening of strawberry fruit*. Horticultural Reviews 17, 267-297.

Pineli, L. d. L. d. O., Moretti, C. L. and Chiarello, M. D. (2012) ‘Quality, bioactive compounds and antioxidant activity of strawberries grown in the Brazilian savannah and stored at different temperatures’, *Journal of Food, Agriculture and Environment*, **21**, (1), 38-41.

Pyrotis, S., Abayomi, L., Rees, D. and Orchard, J. (2012) ‘Effect of temperature and humidity on strawberry firmness at two different sites in the Huelva region of Spain’, *Acta Horticulturae*, **962**, 567-570.

Rahman, M. M., Rahman, M. M., Hossain, M. M., Khaliq, Q. A. and Moniruzzaman, M. (2014). ‘Effect of planting time and genotypes growth, yield and quality of strawberry (*Fragaria* x *ananassa* Duch.)’, *Scientia Horticulturae*, **167**, 56-62.

Ranathunga, C. L., Jayaweera, H. H. E., Suraweera, S. K. K., Wattage, S. C., Ruvinda, K. K. D. L. and Ariyaratne, T. R. (2010) ‘Vibration effects in vehicular road transportation’ Proceedings of the 26th Technical Sessions, Institute of Physics, Colombo, Sri Lanka, March 2010, 9-16.

Rediers, H., Claes, M., Peeters, L. and Willems, K. A. (2009) ‘Evaluation of the cold chain of fresh-cut endive from farmer to plate’, *Postharvest Biology and Technoogy*, **51**, 257-262.

Reza, T. (2013) ‘Engineering properties and bruise susceptibility of peach fruits’, *Agricultural Engineering International: CIGR Journal*, **15**, (4), 244-252.

Rissi, G. O., Singh, S. P., Burgess, G. and Singh, J. (2008) ‘Measurement and analysis of truck transport environment in Brazil’, *Packaging Technology and Science*, **21**, 231-246.

Robinson, J. E., Browne, K. M. and Burton, W. G. (1975) ‘Storage characteristics of some vegetables and soft fruits’, *Annals of Applied Biology*, **81**, 399-408.

Ruiz-Altisent, M. and Moreda, G. P. (2011) ‘Fruits, mechanical properties and bruise susceptibility’, in J. Gliński, J. Horabik and J. Lipiec (ed.), *Encyclopedia of Agrophysics*. Dordrecht: Springer, 318-321.

Rural Payments Agency (RPA) (2011) *Commission implementing regulation (EU) No 543/2011* [www.document]. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/299247/Strawberries.pdf (Accessed 13 April 2015).

Russell, L. F., LeBlanc, D. I., McRae, K. B. and Ryan, D. A. J. (2009) 'Losses of vitamin C from fresh strawberries in a commercial supply chain', *International Journal of Food Science and Technology*, **44**, 820-828.

RW Walpole (2014) *Plant success 2013-2014* [www.document]. http://www.rwwalpole.co.uk/downloads/2013-14%20catalogue.pdf (Accessed 13 April 2015).

Sacks, E. J. and Shaw, D. V. (1993) 'Color change in fresh strawberry fruit of seven genotypes stored at $0^{o}C$', *HortScience*, **28** (3), 209-210.

Saha, K., Singh, S. P. and Harte, B. (2009) 'Effect of transport vibration on quality of minimally processed and packaged fresh-cut cantaloupe', *Journal of Applied Packaging Research*, **3**, (1), 15-26.

Salamat, R., Ghassemzadeh, H. R., Heris, S. S. S. and Hajilou, J. (2013) 'Determination of appropriate harvesting time for strawberry to enhance its flavor index and reduce bruising susceptibility', *International Journal of Agronomy and Plant Production*, **4**, (8), 1969-1977.

Saltveit, M. E. (2002) 'The rate of ion leakage from chilling-sensitive tissue does not immediately increase upon exposure to chilling temperatures'. *Postharvest Biology and Technology*, **26**, 295-304.

Salviet, M. E. (2015) *Measuring respiration* [www.document]. http://ucce.ucdavis.edu/files/datastore/234-20.pdf (Accessed 13 April 2015).

Samim, W. and Banks, N. H. (1993) 'Colour changes in bruised apple fruit tissue', *New Zealand Journal of Crop and Horticultural Science*, **21**, 367-372.

Sanford, K. A., Lidster, P. D., McRae, K. B., Jackson, E. D., Lawrence, R. A., Stark, R. and Prange, R. K. (1991) 'Lowbush blueberry quality changes in response to mechanical damage and storage temperature', *Journal of the American Society for Horticultural Science*, **116**, (1), 47-51

Sanz, C., Olías, R. and Pérez, A. G. (2002) 'Quality assessment of strawberries packed with perforated polypropylene punnets during cold storage', *Food Science and Technology International*, **8**, (2), 65-71.

Sanz, C., Pérez, A. G., Olías, R. and Olías, J. M. (1999) 'Quality of strawberries packed with perforated polypropylene', *Journal of Food Science*, **64**, (4), 748-752.

Saracoglu, T., Ucer, N. and Ozarslan, C. (2011) 'Engineering properties and susceptibility to bruising damage of table olive (*Olea europaea*) fruit', *International Journal of Agriculture and Biology*, **13**, 801-805.

Scalia La, G., Alello, G., Miceli, A., Nasca, A., Alfonzo, A. and Settanni, L. (2015) 'Effect of vibration on the quality of strawberry fruits caused by simulated transport', *Journal of Food Process Engineering*, 1-15.

Schoorl, D. and Holt, J. E. (1980) 'Bruise resistance measurements in apples', *Journal of Texture Studies*, **11**, 389-394.

Segovia-Bravo, K. A., García-García, P., López- López, A. and Garrido-Ferńandez, A. (2011) 'Effect of bruising on respiration, superficial color, and phenolic changes in fresh manzanilla olives (*Olea europaea pomiformis*): development of treatments to mitigate browning', *Journal of Agricultural and Food Chemistry*, **59**, 5456-5464.

Sek, M. A. (1996) 'A modern technique of transportation simulating for package performance testing', *Packaging Technology and Science*, **9**, 327-343.

Shafie, M. M., Rajabipour, A. Castro-García, S., Jiménez-Jiménez, F. and Mobli, H. (2015) 'Effect of fruit properties on pomegranate bruising', *International Journal of Food Properties,* **18**, (8), 1837-1846.

Shahbazi, F., Rajabipour, A., Mohtasebi, S. and Rafie, Sh. (2010) 'Simulated In-transit vibration damage to watermelons', *Journal of Agricultural Science and Technology,* **12**, 23-24.

Sharan, G., Srivastav, S., Rawale, K. P. and Dave, U. (2009) 'Development of corrugated fiber board cartons for long distance transport of tomatoes in India', *International Journal of Service Learning in Engineering,* **4**, (1), 31-43.

Shewfelt, R. L. (1999) 'What is quality?', *Postharvest Biology and Technology,* **15**, 197-200.

Shin, Y, Liu, R. H., Nock, J. F., Holliday, D. and Watkins, C. B. (2007) 'Temperature and relative humidity effects on quality, total ascorbic acid, phenolics and flavonoid concentrations, and antioxidant activity of strawberry', *Postharvest Biology and Technology,* **45**, 349-357.

Shin, Y., Ryu, J. A., Liu, R. H., Nock, J. F. and Watkins, C. B. (2008) 'Harvest maturity, storage temperature and relative humidity affect fruit quality, antioxidant contents and activity, and inhibition of cell proliferation of strawberry fruit', *Postharvest Biology and Technology*, **49**, 201-209.

Singh, J. and Singh, S. P. (2007) 'Damage reduction to food products during transportation and handling', in M. Kutz (ed.), *Handbook of Farm Dairy, and Food Machinery*. New York: William Andrew, Inc, 655-693.

Singh, J., Kisch, R., Chhun, J. and Olsen E. (2009) 'Design-An opportunity in reducing corrugated fiberboard carbon footprint', *Journal of Applied Packaging Research,* **3**, (2), 105-118.

Singh, J., Singh, S. P. and Joneson, E. (2006) 'Measurement and analysis of US truck vibration for leaf spring and air ride suspensions, and development of tests to simulate these conditions', *Packaging Technology and Science,* **19**, 309-323.

Singh, R., Shama, R. R. and Tyagi, S. K. (2007a) ‘Pre-harvest foliar application of calcium and boron influences physiological disorders, fruit yield and quality of strawberry (*Fragaria* x *ananassa* Duch.), *Scientia Horticulturae*, **112**, 215-220.

Singh, S. P., Sanhu, A. P. S., Singh, J. and Joneson, E. (2007b) ‘Measurement and analysis of truck and rail shipping environment in India’, *Packaging Technology and Science*, **20**, 381-392.

Sinobas, L. R., Ruiz-Altisent, M. and de la Perez, J. L. (1991) ‘Bruise development and fruit response of pear (cv. 'Blanquilla') under impact conditions’, *Journal of Food Engineering*, **14**, 289-301.

Slaughter, D. C., Hinsch, R. T. and Thompson, J. F. (1993) ‘Assessment of vibration injury to Bartlett pears’, *Transactions of the ASAE (American Society of Agriculture Engineers)*, **36**, (4), 1043-1047.

Smith, J. P., Zagory, D. and Ramaswamy, H. S. (2004) ‘Packaging of fruits and vegetables’ in D. M. Barrett, L. Somogyi and H. Ramaswamy (ed.), *Processing fruits: Science and Technology Florida (2nd edition)*, New York: CRC Press, 355 -395.

Soleimani, B. and Ahmadi, E. (2014) ‘Measurement and analysis of truck vibration levels as a function of packages locations in truck bed and suspension’, *Computers and Electronics in Agriculture*, **109**, 141-147.

Sommer, N. F., Fortkage, R. J. and Edwards, D. C. (2002) ‘Postharvest Diseases of Selected Commodities’, in A.A. Kader (ed.), *Postharvest Technology of Horticultural Crops* (3rd edition). Oakland: University of California, Division of Agriculture and Natural Resources, 197-249.

Spornberger, A., Weissinger, H., Steffek, R., Scheiblauer, J., Jezik, K., Altennurger, J. and Stich, K. (2008) *Result from a three year testing project of new strawberry cultivars in Verticillium infested soils and under organic farming conditions* [www.document]. http://orgprints.org/13657/ (Accessed 13 July 2015).

Strawberry (2016) *Strawberry picking* [www.document]. http://strawberryplants.org/2010/06/strawberry-picking/ (Accessed 27 February 2017).

Stuart, T. (2009). *Waste: Uncovering the Global Food Scandal*. London: Penguin Books.

Studman, C. J., Brown, G. K., Tim, E. J., Schulte, N. L. and Vreede, M. J. (1997) 'Bruising on blush and non-blush sides in apple-to-apple impacts', *Transactions of the ASAE (American Society of Agriculture Engineers),* **40** (6), 1655-1633.

Sturm, K., Koron, D. and Stampar, F. (2003) 'The composition of fruit of different strawberry varieties depending on maturity stage', *Food Chemistry,* **83**, 417-422.

Tabatabaekoloor, R., Heshemi, S. J. and Taghizade, G. (2013) 'Vibration damage to kiwifruits during road transportation', *International Journal of Agriculture and Food Science Technology*, **4**, (5), 467-474.

Talcott, S. T. (2007) 'Chemical components of berry fruits', in Y. Zhao (ed.), *Berry Fruit Value-Added Products for Health Promotion*. Florida: CRC Press, 51-72.

Terry, L. A. (2012) 'Soft fruit', in D. Rees, G. Ferrell and J. Orchard (ed), *Crop Post-Harvst: Science and Technology, Perishable*s. West Sussex: Wiley-Blackwell, 227-246.

Terry, L. A., Crisosto, C. H. and Forney, C. F. (2009) 'Small Fruit and Berries', in E. M. Yahia (ed.), *Modified and Controlled Atmospheres for the Storage, Transportation, and Packaging of Horticultural Commodities*. Florida: CRC Press, 364-396.

Terry, L. A., Joyce, D. C., Adikaram, N. K. B. and Khambay, B. P. S. (2004) Preformed antifungal compounds in strawberry fruit and flowers. *Postharvest Biology and Technology*. **31**, 201–212.

Terry, L. A., Mena, C., Williams, A. and Whitehead, P. (2011) *Fruit and vegetable resource maps: Mapping fruit and vegetable waste through the retail and wholesale supply chain*. WRAP, RC008.

Testoni, A., Lovatti, L. and Faedi, W. (1989) 'Shelf life and fruit quality of strawberry varieties and selections after storage', *Acta Horticulturae,* **265**, 435-442.

The UK government (2014) *Speed limits* [www document]. https://www.gov.uk/speed-limits (Accessed 15 March 2015).

Thompson, J. and Knutson., J. (1997) 'Forced air cooling of strawberries in clamshell baskets', *Perishables Handling Newsletter,* **90**, 29-30.

Thompson, J. F. (2002a) 'Storage system', in A. A. Kader (ed.), *Postharvest Technology of Horticultural Crops* (3rd edition). Oakland: University of California, Division of Agriculture and Natural Resources, 113-128.

Thompson, J. F. (2002b) 'Transportation', in A. A. Kader (ed.), *Postharvest Technology of Horticultural Crops* (3rd edition). Oakland: University of California, Division of Agriculture and Natural Resources, 259-269.

Thompson, J. F. (2002c) 'Harvesting system', in A. A. Kader (ed.), *Postharvest Technology of Horticultural Crops* (3rd edition). Oakland: University of California, Division of Agriculture and Natural Resources, 63-65.

Thompson, J. F. (2014) *Pre-cooling and Storage Facilities* [www document] http://www.ba.ars.usda.gov/hb66/precooling.pdf (Accessed 17 August 2015).

Thompson, J. F. and Mitchell, F. G. (2002) 'Packages for Horticultural Crops', in A.A. Kader (ed.), *Postharvest Technology of Horticultural Crops* (3rd edition). Oakland: University of California, Division of Agriculture and Natural Resources, 85-95.

Thompson, J. F., Mitchell, F. G. and Kasmire, R. F. (2002) 'Cooling Horticultural Commodities', in A.A. Kader (ed.), *Postharvest Technology of Horticultural Crops* (3rd edition). Oakland: University of California, Division of Agriculture and Natural Resources, 97-128.

Thompson, J. F., Mitchell, F. G., Rumse, T. R., Kasmire, R. F. and Crisosto, C. H. (1998) ‘Commercial cooling of fruits, vegetables and flowers’. Oakland: University of California, Division of Agriculture and Natural Resources 21567.

Timm, E. J., Brown, G. K. and Armstrong, P. R. (1996) ‘Apple damage in bulk bins during semi-trailer transport’, *Applied Engineering in Agriculture*, **12**, (3), 369-377.

Toivonen, P. M. A., Hampson, C., Stan, S., McKenzie, D. L. and Hocking, R. (2007) ‘Factors affecting severity of bruises and degree of apparent bruise recovery in a yellow-skinned apple’ *Postharvest Biology and Technology*, **45**, 276-280.

Underhill, S. J. R., Mclauchlan, R. L. and Dahler, J. M. (1998) ‘Flavedo and albedo changes in ‘Eureka’ lemons caused by static compression and impact loading’, *Journal of Texture Studies*, **29**, 437-452.

United Nation Economic Commission for Europe (UNECE) (2010) *Strawberries* [www document] http://www.unece.org/fileadmin/DAM/trade/agr/standard/fresh/FFV-Std/English/35Strawberries_2010.pdf (Accessed 13April 2015).

United States Department of Agriculture (USDA) (2006) *United States Standards for Grades of Strawberries* [www document] http://www.ams.usda.gov/AMSv1.0/getfile?dDocName=STELPRDC5050392 (Accessed 31 January 2013).

Unuigbe, O. M. and Onuoha, S. N. (2013) ‘Assessment of impact damage to apple fruits’, *Nigerian Journal of Technology*, **32**, (1), 137-140.

US Department of Agriculture, Agriculture Research Service. (2012) *USDA national nutrient for standard references, release 25. Fruits and fruit juices* [www document] http://ndb.nal.usda.gov/ndb/search/list (Accessed 31 January 2013).

Van Zeebroeck, M., Darius, P., De Ketelaere, B., Ramon, H., Tijskens, E. (2007a). The effect of fruit factors on the bruise susceptibility of apples. *Postharvest Biology and Technology*, **46**, 10-19.

Van Zeebroeck, M., Van linden, V., Darius, P., De Ketelaere, B., Ramon, H. and Tijskens, E. (2007b) 'The effect of fruit properties on the bruise susceptibility of tomatoes', *Postharvest Biology and Technology*, **45**, 168-175.

Vergano, P. J., Testin, R. F. and Newall, W. C. (1991) 'Peach bruising: Susceptibility to impact, vibration, and compression abuse', *Transactions of the ASAE (American Society of Agriculture Engineers),* **34**, (5), 2110-2116.

Vicente, A. R., Marti´nez, G.A., Chaves, A. R. and Civello, P.M. (2002) 'Quality of heat-treated strawberry fruit during refrigerated storage', *Postharvest Biology and Technology,* **25**, 59-71.

Vigneault, C. (2005) 'Transport of fruits and vegetables', *Stewart Postharvest Review*, **1**, (6), 1-4.

Vigneault, C., Hui, C. K. P., LeBlanc, D. I., DeEll, J. R. and Sotocinal, S. A. (2003) 'Transportation and handling of fresh fruits and vegetables', in A. Chakravery, A. S. Mujumdar, G. S. Raghavan and H. S. Ramaswamy (ed.), *Handbook of Postharvest Technology: Cereals, Fruits, Vegetables, Tea, and Spices*. New York: Marcel Deker, Inc., 555-584.

Vigneault, C., Thompson, J., Wu, S., Hui, K. P. C. and LeBlanc, D. I. (2009) 'Transportation of horticultural produce', *Postharvest Technologies for Horticultural Crops*, **2**, 1-24.

Villahermosa, A. A. S., Bihn, L. N., Rolle, R. S. and Chonhenchob, V. (2011) *Packaging in fresh produce supply chain in Southeast Asia*. Bangkok: Food and Agriculture Organization of the United Nations, RAP Publication 2011/20.

Vursavuş, K. and Özgüven, F. (2004) 'Determining the effects of vibration parameters and packaging method on mechanical damage in Golden Delicious apples', *Turkish Journal of Agriculture and Forestry*, **28**, 311-320.

Whitlow, T. H., Bassuk, N., Ranney, T. G. and Reichert, D. L. (1992) 'An improved method for using electrolyte leakage to assess membrane competence in plant tissues' *Plant Physiology*, **98**,198-205.

William, A. G., Pell, E., Webb, J., Tribe, E., Evans, D., Moorhouse, E. and Watkiss, P. (2008) *Final Report for Defra Project FO0103, Comparative Life Cycle Assessment of Food Commodities Procured for UK Consumption through a Diversity of Supply Chains* [www.document]. http://randd.defra.gov.uk/Default.aspx?Module=More&Location=None&ProjectID=15001 (Accessed 20 April 2013).

William, M., Water, Jr., Randall-Schadel, B. and Schadel, W. E. (1990) 'Wound healing in cucumber fruit', *Journal of the American Society for Horticultural Science*, **115**, (3), 444-452.

Wills, R. B. H., McGlasson, W. B., Graham, D. and Joyce, D. C. (2007) *Postharvest: An introduction to the physiology and handling of fruit, vegetables and ornamentals* (5^{th} edition). Sydney: University of New South Wales Press Ltd.

Yu, P., Li, C., Takeda, F. and Krewer, G. (2014) 'Visual bruise assessment and analysis of mechanical impact measurement in southern high bush blueberries', *Applied Engineering in Agriculture*, **30**, (1), 29-37.

Yuan, B. Z., Sun, J. and Nishiyama, S. (2004) 'Effect of drip irrigation on strawberry growth and yield inside a plastic greenhouse', *Biosystem Engineering*, **87**, (2), 257-245.

Zagory, D *and* Kader, A. A. (1988) 'Modified atmosphere packaging of fresh produce', *Food Technology*, **42**, (9), 70-77.

Zarifneshat, S., Ghassemzadeh, H. R., Sadeghi, M., Abbaspour-Fard, M. H., Ahmadi, E., Javadi, A. and Shervani-Tabar, M. T. (2010) 'The effect of impact and fruit properties on the bruising of peach', *American Journal of Agricultural and Biological Sciences*, **5**, (2), 114-121.

Zeebroeck, M. V., Lombaert, G., Dintwa, E., Ramon, H., Degrande, G. and Tijakens, E. (2008) ‘The simulation of the impact damage to fruit during the passage of a truck over a speed bump by means of the discrete element method’, *Biosystems Engineering*, **101**, 58-68.

Zhang, W. (1994) Apple impact bruise analysis. Unpublished PhD dissertation. Washington State: Washington State University.

Zhou, R., Su, S., Yan, L. and Li, Y. (2007) ‘Effect of transport vibration levels on mechanical damage and physiological responses of Huanghua pears (*Pyrus pyrifolia* Nakai cv. Huanghua)’, *Postharvest Biology and Technology*, **46**, 20-28.

APPENDICES

1. INFORMATION OF TWELVE SHIPMENTS ON THE LONDON AND MANCHESTER ROUTES

Appendix 1.1: Delivery information of shipment 1on the WC100 route.

Location	Place	Distance (km)	Duration (min)	Average speed (km/hr)
	Shipment 1-WC100 (22/7/2014)			
CASE A				
L0	Reynolds			
L1	Benugo Shoreditch Baker & Benugo CPU Bermondsey	37.677	46	48.2
	Unloading	0	11	0.0
L2	Inn or Out LTD	2.791	9	24.9
	Unloading	0	3	0.0
L3	SSP Main Stores, Waterloo	7.466	25	30.8
	Unloading	0	25	0.0
	Total (Travelling transport)[a]	**47.934**	**80**	**34.6**
CASE B				
L4	Ping Pong (Southbank)	1.446	5	21.9
	Unloading	0	6	0.0
L5	Yo-Sushi Southbank Cent & Giraffe Southbank	0.178	2	91.0
	Total (Travelling transport)[a]	**1.624**	**7**	**56.4**

[a] The period of unloading is not included.

Appendix 1.2: Delivery information of shipment 2 on the WC100 route .

Shipment 2-WC100 (25/7/2014)				
Location	**Place**	**Distance (km)**	**Duration (min)**	**Average speed (km/hr)**
CASE A				
L0	Reynolds			
L1	Inn or Out LTD	38.637	52	45.7
	Unloading	0	11	0.0
L2	Benugo Shoreditch Baker & Benugo CPU Bermondsey	2.959	5	29.8
	Unloading	0	19	0.0
L3	SSP Main Stores, Waterloo	6.767	18	28.6
	Unloading	0	19	0.0
L4	Ping Pong (Southbank)	0.610	3	21.6
	Unloading	0	8	0.0
L5	Yo-Sushi Southbank Cent & Giraffe Southbank	0.158	2	25.5
	Total (Travelling transport)[a]	**49.131**	**80**	**30.2**

[a] The period of unloading is not included.

Appendix 1.3: Delivery information of shipment 3 on the WC100 route .

Shipment 3-WC100 (29/8/2014)				
Location	**Place**	**Distance (km)**	**Duration (min)**	**Average speed (km/hr)**
CASE A				
L0	Reynolds			
L1	Inn or Out LTD	39.973	47	44.6
	Unloading	0	19	0.0
L2	Benugo Shoreditch Baker & Benugo CPU Bermondsey	3.269	6	27.6
	Total (Travelling transport)[a]	**43.242**	**53**	**36.1**

[a] The period of unloading is not included.

Appendix 1.4: Delivery information of shipment 4 on the WC109 route.

Shipment 4-WC109 (28/5/2014)				
Location	**Place**	**Distance (km)**	**Duration (min)**	**Average speed (km/hr)**
CASE A				
L0	Reynolds			
L1	SSP Vitoria Railway Station & SSP-Camden Food Victoria Station	42.095	49	47.30
	Unloading	0	8:02	0
L2	Gaucho-Freggo & Gaucho-Piccadilly	3.151	7	27.0
	Total (Travelling transport) [a]	**45.246**	**56**	**37.1**

[a] The period of unloading is not included.

Appendix 1.5: Delivery information of shipment 5 on the WC109 route.

Shipment 5-WC109 (20/6/2014)				
Location	**Place**	**Distance (km)**	**Duration (min)**	**Average speed (km/hr)**
CASE B				
L3	Gaucho Piccadilly			
L4	Hyatt Regency Churchill London & Radissons London Portman SQ	1.974	10	22.6
	Unloading	0	89	0
L5	Rainforest Cafe	3.649	19	29.7
	Total (Travelling transport) [a]	**5.623**	**29**	**26.2**

[a] The period of unloading is not included.

Appendix 1.6: Delivery information of shipment 6 on the WC109 route.

Shipment 6-WC109 (4/7/2014)				
Location	**Place**	**Distance (km)**	**Duration (min)**	**Average speed (km/hr)**
CASE A				
L0	Reynolds			
L1	SSP Victoria Railway Station & SSP-Camden Food Victoria Station	42.341	60	37.6
	Total (Travelling transport) [a]	**42.341**	**60**	**37.6**

[a] The period of unloading is not included.

Appendix 1.7: Delivery information of shipment 7 on the WC109 route.

Shipment 7-WC109 (7/7/2014)				
Location	**Place**	**Distance (km)**	**Duration (min)**	**Average speed (km/hr)**
CASE A				
L0	Reynolds			
L1	SSP Vitoria Railway Station & SSP-Camden Food Victoria Station	42.266	52	43.9
	Unloading	0	21	0
	Total (Travelling transport) [a]	**45.266**	**52**	**43.9**
CASE B				
L2	Gaucho Piccadilly			
L3	Hyatt Regency Churchill London & Radissons London Portman SQ	1.881	5	24.4
	Total (Travelling transport) [a]	**1.881**	**5**	**24.4**

[a] The period of unloading is not included.

Appendix 1.8: Delivery information of shipment 8 on the WC109 route.

Shipment 8-WC109 (11/7/2014)				
Location	**Place**	**Distance (km)**	**Duration (min)**	**Average speed (km/hr)**
CASE B & C				
L0	Reynolds			
L1	SSP Vitoria Railway Station & SSP-Camden Food Victoria Station	41.992	54	43.3
	Unloading	0	34	0.0
L2	SSP Victoria Coach station, SPP Victoria Coach Delice De France & Whistlestop Victoria Coacourse	0.727	3	19.0
	Unloading	0	30	0.0
L3	Gaucho Piccadilly	3.452	10	27.9
	Unloading	0	25	0.00
L4	Hyatt Regency Churchill London & Radissons London Portman SQ	2.115	7	20.8
	Total (Travelling transport) [a]	**48.286**	**74**	**27.8**

[a] The period of unloading is not included.

Appendix 1.9: Delivery information of shipment 9 on the WC109 route.

Shipment 9-WC109 (14/7/2014)				
Location	**Place**	**Distance (km)**	**Duration (min)**	**Average speed (km/hr)**
CASE B & C				
L0	Reynolds			
L1	SSP Vitoria Railway Station & SSP-Camden Food Victoria Station	42.330	54	43.0
	Unloading	0	31	0
L2	Gaucho Piccadilly	3.085	10	26.0
	Unloading	0	36	0.0
L3	Hyatt Regency Churchill London & Radissons London Portman SQ	2.123	7	27.0
	Total (Travelling transport) [a]	**47.538**	**71**	**32.0**

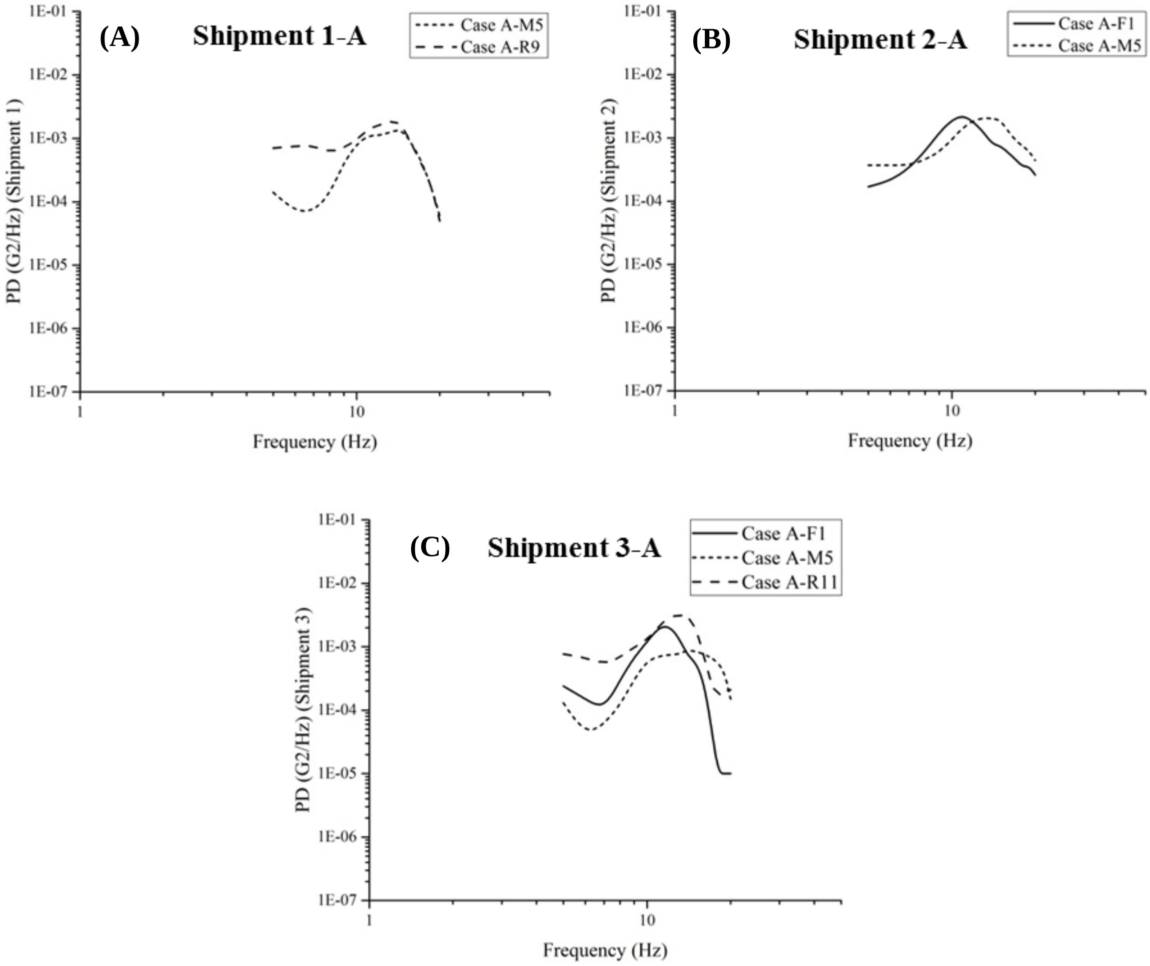
[a] The period of unloading is not included.

Appendix 1.10: Delivery information of shipment 10-12 on the Manchester route.

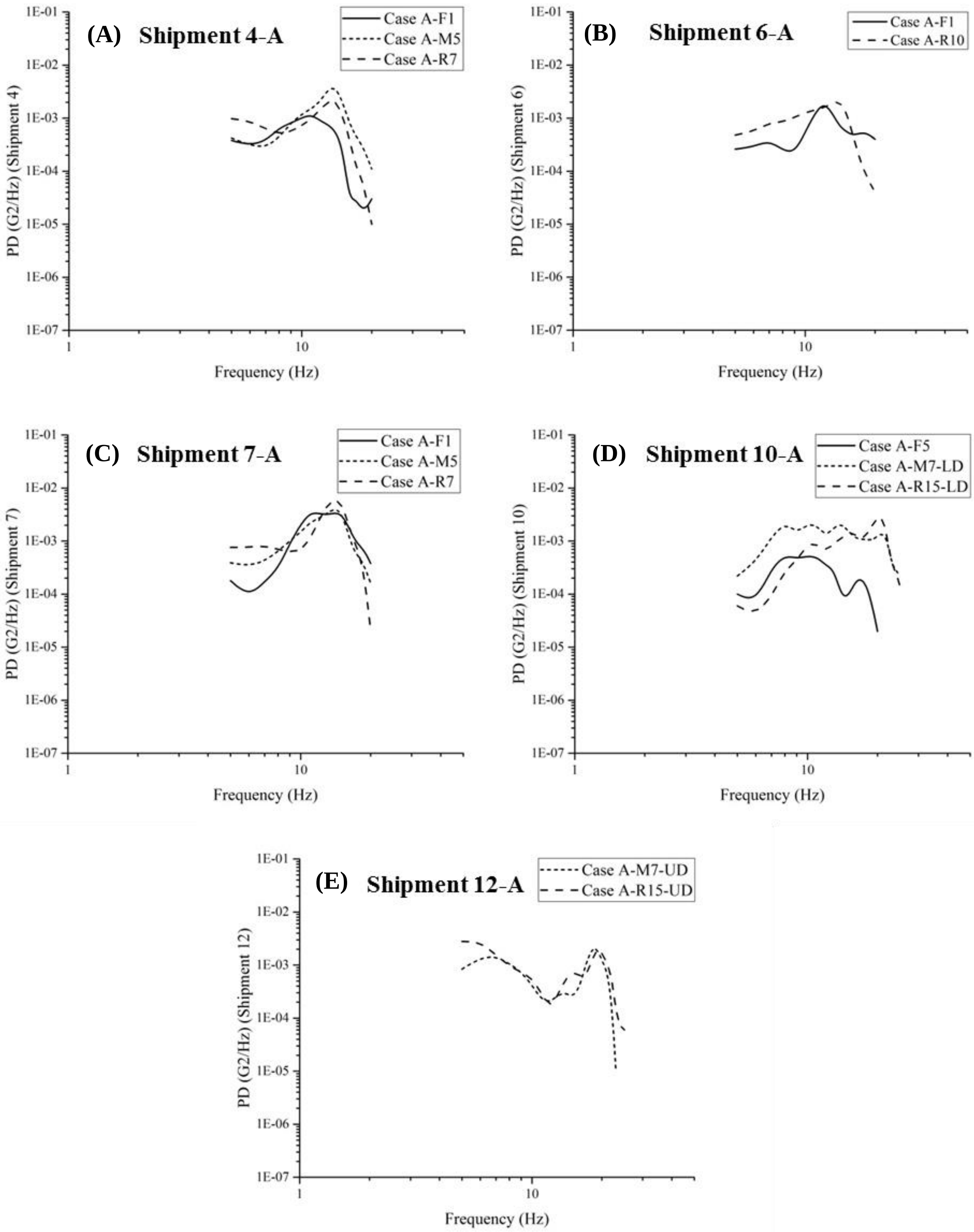
Location	Place	Distance (km)	Duration (min)	Average speed (km/hr)
CASE A Shipment 10 (18/7/2014)				
L0	Reynolds (London)			
L1	Reynolds (Manchester)	314.005	224	75.27
	Total (Travelling transport)[a]	**314.005**	**224**	**75.27**
CASE B & D Shipment 11 (28/7/2014)				
L0	Reynolds (London)			
L1	Reynolds (Manchester)	317.421	222	76.18
	Total (Travelling transport)[a]	**317.421**	**222**	**76.18**
CASE A & B Shipment 12 (1/8/2014)				
L0	Reynolds (London)			
L1	Reynolds (Manchester)	319.550	273	67.65
	Total (Travelling transport)[a]	**319.550**	**273**	**67.65**

[a] The period of unloading is not included.

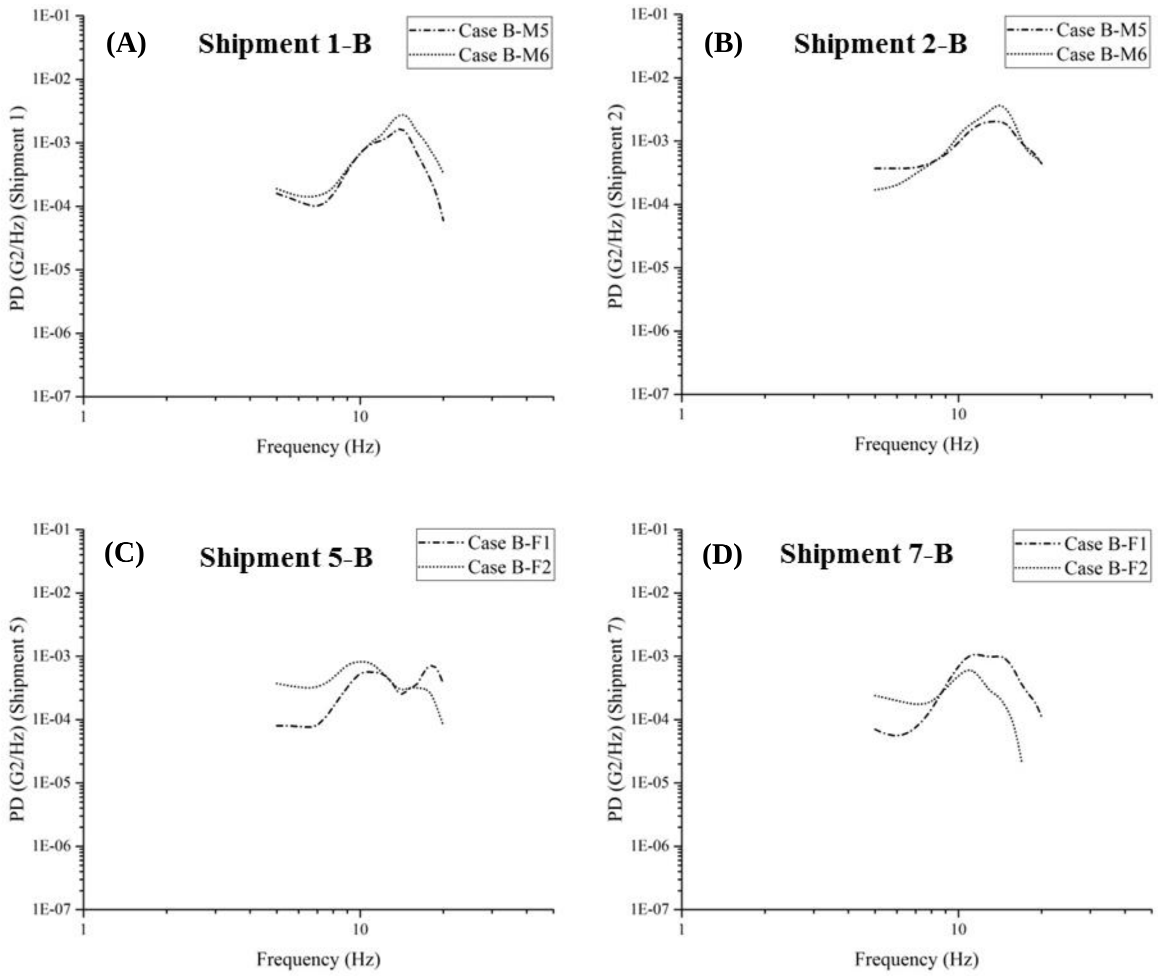
2. POWER DENSITY (PD) SPECTRA OF FOUR CASES FROM 12 SHIPMENTS



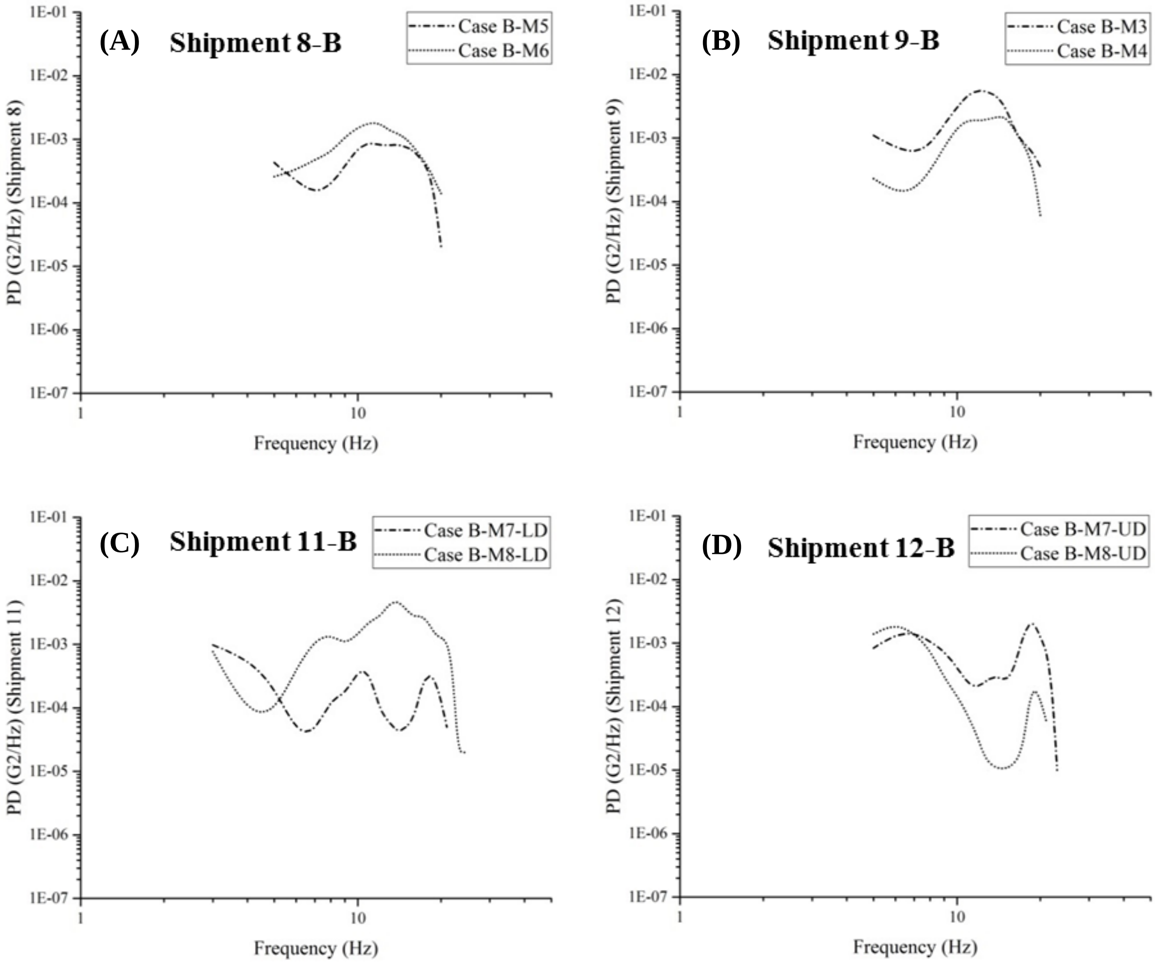
Appendix 2.1: Power Density (PD) spectra of case A from shipment 1 (A), 2 (B) and 3 (C) on the WC100 route.



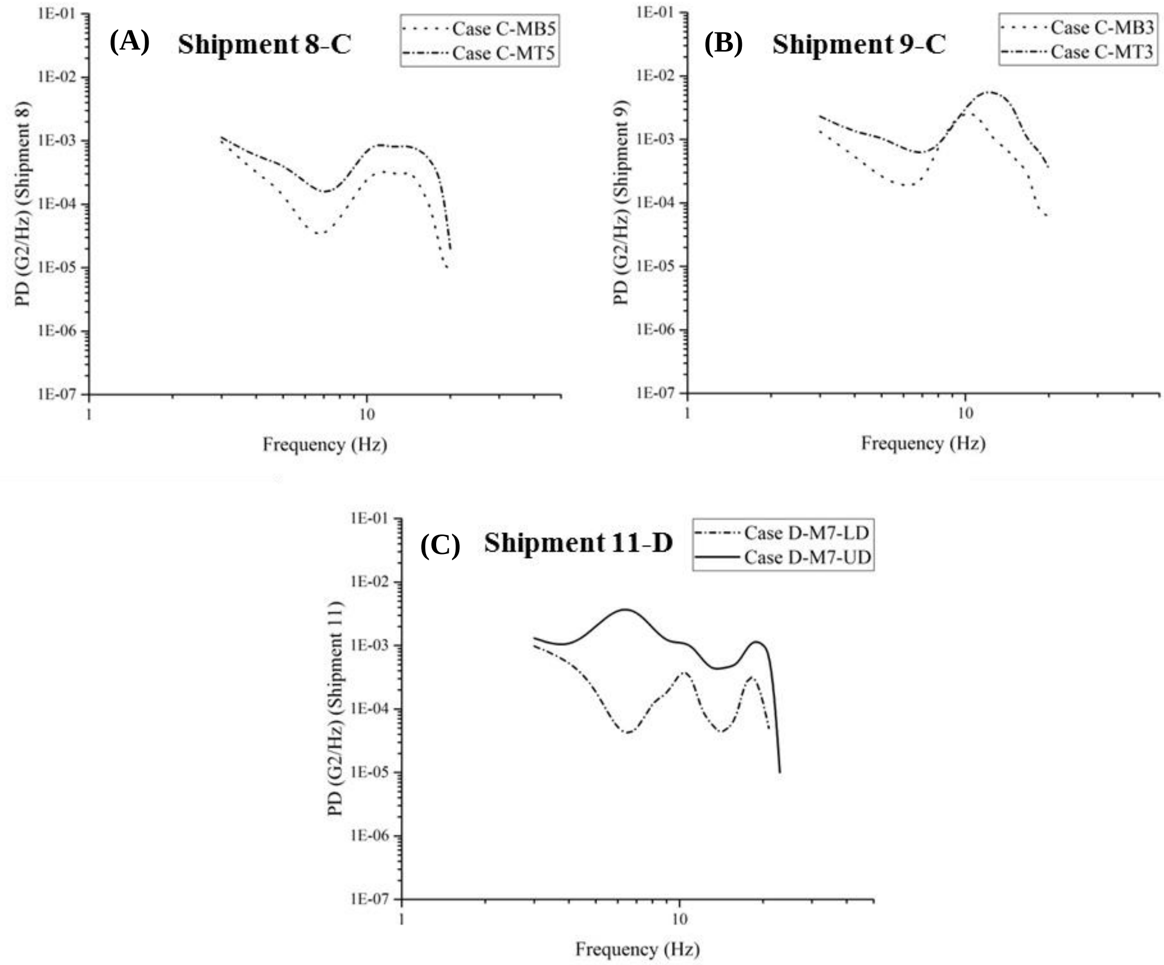
Appendix 2.2: Power Density (PD) spectra of case A from shipment 4 (A), 6 (B), 7 (C), 10 (D) and 12 (E). The shipments (4-7) and (10-12) were studied on the WC109 and Manchester routes, respectively.



Appendix 2.3: Power Density (PD) spectra of case B from shipment 1 (A), 2 (B), 5 (C) and 7 (D). The shipments (1,2) and (5,7) were studied on the WC100 and WC109 routes, respectively.



Appendix 2.4: Power Density (PD) spectra of case B from shipment 8 (A), 9 (B), 11 (C) and 12 (D). The shipments (8,9) and (11,12) were studied on the WC109 and Manchester routes, respectively.



Appendix 2.5: Power Density (PD) spectra of case C from shipment 8 (A) and 9 (B), and the case D on the WC109 route and from shipment 11 (C) on the Manchester route.

3. Physical properties of 'Elsanta' and 'Sonata' strawberries

Appendix 3.1: Fruits mass, geometric attributes, fruit shape index, ellipsoid ratio, roundness and fruit firmness of 'Elsanta' and 'Sonata' strawberries in the winter cultivation 2015.

Parameter	**Elsanta**	**Sonata**
Fruits mass (g)	17.12±0.48	18.67±0.63
Length (L) (mm)	33.95±0.56	34.52±0.53
Major lateral diameter (D1) (mm)	34.83±0.41	35.80±0.45
Minor lateral diameter (D1) (mm)	32.69^{b}±0.43	34.06^{a}±0.49
Average diameter (D) (mm)	33.76±1.77	34.93±0.01
Fruit shape index (L/D)	1.00±0.15	0.98±0.01
Roundness ($L1/\sqrt{D1}D2$)	0.059±0.001	0.057±0.001
Ellipsoid ratio (D1/D2)	1.06±0.010	17.12±0.008
Firmness (kg)	0.512±0.168	0.544±0.017

Means with different letters in the same row for t-test are significantly different at $p<0.05$. Values are the mean ±S.E. from 20 replicates (n=20).

Appendix 4.2: The published journal: Chaiwong, S. and Bishop, C. F. H. 2015. 'Effect of vibration damage on the storage quality of 'Elsanta' strawberry', *Australian Journal of Crop Science*, **9**, (9), 859-864.

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Effect of vibration damage on the storage quality of 'Elsanta' strawberry

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Abstract

Vibration tests were carried out on strawberry punnets at three frequency levels of 3, 4 and 5 Hz for 50 and 150 sec. 'Elsanta' strawberries were packed in 250 g polyethylene terephthalate (PET) punnets for the vibration test. Strawberry quality was determined immediately after vibration test on the initial day and after storage at 10°C (±1°C) and 70% RH (±5%RH) for 3 days. Strawberries in the punnets were evaluated for percentage of quality categories, severity bruise, electrical conductivity (EC), firmness as well as total soluble solids (TSS) and titratable acidity (TA). EC value and percentage of the dry bruise showed an increase with frequency level and time. The frequency at 5 Hz for 150 sec was the critical vibration for an increase of bruise and EC value and a reduction of severity score ($p<0.05$). No significant differences were observed among TSS and TA submitted to different frequency and time of the vibration test. The conductivity values were also highly associated with the severity of the bruises (r= -0.764) while there was no significant relationship between conductivity and firmness on the initial day. Results indicated that the electrical conductivity evaluation in the vibration test of strawberries can be used as a rapid evaluation method to assess strawberry bruises during the handling and transportation.

Keywords: bruise, firmness, vibration, strawberries.
Abbreviations: EC_electrical conductivity; PET_polyethylene terephthalate; r_ correlation coefficient; TSS_ total soluble solids; TA_ titratable acidity.

Introduction

Strawberries (*Fragaria × ananassa*) are the most important crop for the soft fruit industry in the UK and account for approximately 25% of total home production of UK fruit in value terms (Department for Environment Food and Rural Affairs, 2013). 'Elsanta' strawberry is the main cultivar used to supply the UK market for around 8 months (April to November) of the year (Fresh Produce Journal, 2012). The main causes of strawberry waste are mechanical damage when in the punnet, poor cool chain systems, mould, rot and different interpretations on specification by different suppliers (Terry et al., 2011). The most common form of mechanical injury on strawberries is compression damage, followed in importance by impact and vibration (abrasion) injuries (Smith et al., 2005). Most minimum requirements of strawberry standard define the appearance as undamaged by bruising and free from damage caused by pests or disease (Ministry of Agriculture, Fisheries and Food, 1996; Organisation for Economic Co-Operation and Development, 2005). The three factors that influence vibration testing on strawberries are frequency (Hz), exposure time (sec) and acceleration (g). Nakamura et al. (2007) found that in a vibration test of 'Tochiotome' strawberries it was a frequency of 7 Hz and acceleration of 1 g for 60 sec that caused a significant increase of bacterial growth at 25°C. Fischer et al. (1992) also reported the critical frequency at the range of 5 to 10 Hz at an acceleration of 0.6 g for 600 sec caused serious damage to 'Selva' strawberries. During strawberry transport, the frequencies of truck vibration of 3.35, 7 and 13.5 Hz with acceleration level of 0.02 to 0.19 g were found as the cause of strawberry damage under standard road conditions (Kojima et al, 1999).

Many attempts have been made to evaluate strawberry bruises but it is generally assessed by visual quality using a visual rating scale. The bruise severity of an individual strawberry is graded by the bruise diameter and percent of bruise area (Fischer et al., 1992). The number of strawberry bruises was assessed inside a package by severity scales from 5 (very good = no sign of bruise) to 1 (very severely damage = whole fruit bruised) (Pelletier et al., 2011). The calculation of bruise volume was assumed to be a cone shape ($1/3\Pi [w/2]^2 D$)), where w = bruise width; D = bruise depth (Ferreira et al., 2008). These assessment methods require a great deal of time to have any accuracy as a large number of fruit must be accessed and a more rapid method is required. Electrical conductivity is a technique for the possible evaluation of postharvest strawberry damage. Jiang et al. (2001) found that the significant correlation between the conductivity and the percent pared fruit (r=0.938) or damage indexes of strawberries (r=0.917). The strawberry firmness directly affects the susceptibility to physical and mechanical injuries (Kader, 1999). However, very little is known about the correlation between vibration level and strawberry firmness. For example, Fischer et al. (1992) found that vibration level had no effect on strawberry firmness. There has been no study in the relationship between the electrical conductivity and the firmness of strawberry bruise. The objectives of the present research were firstly to examine vibration test in 'Elsanta' strawberries at 3, 4 and 5 Hz for periods of 50 and 150 sec and secondly to determine the strawberry damage and quality after the vibration test and after storage at 10°C for 3 days.

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Table 1. Percentage of quality category and severity bruise score of 'Elsanta' strawberries at day 0 and 3 after vibration test at 3, 4 and 5 Hz for 50 and 150 sec.

Treatment	Undamaged (%)	Dry Bruise (%)	Wet Bruise (%)	Severity score
Day 0				
Control	$100.00^{a}\pm0.00$	$0.00^{e}\pm0.00$	$0.00^{b}\pm0.00$	$5.0^{a}\pm0.04$
3Hz-50 sec	$84.56^{b}\pm0.85$	$11.24^{e}\pm2.91$	$4.20^{b}\pm3.00$	$4.8^{a}\pm0.03$
3Hz-150 sec	$61.90^{c}\pm8.86$	$38.10^{c}\pm3.95$	$0.00^{b}\pm0.00$	$4.8^{a}\pm0.05$
4Hz-50 sec	$87.24^{b}\pm7.21$	$9.56^{e}\pm3.15$	$3.20^{b}\pm1.96$	$4.8^{a}\pm0.04$
4Hz-150 sec	$38.86^{d}\pm11.24$	$56.40^{b}\pm5.63$	$4.74^{b}\pm3.11$	$4.7^{a}\pm0.06$
5Hz-50 sec	$72.38^{c}\pm9.11$	$24.62^{d}\pm2.65$	$3.00^{b}\pm1.85$	$4.7^{a}\pm0.04$
5Hz-150 sec	$15.28^{e}\pm10.95$	$71.06^{a}\pm5.82$	$13.65^{a}\pm4.32$	$4.2^{b}\pm0.13$
Day 3				
Control	$56.52^{a}\pm5.38$	$43.48^{d}\pm5.38$	0.00 ± 0.00	$4.6^{a}\pm0.08$
3Hz-50 sec	$23.00^{c}\pm6.48$	$74.40^{bc}\pm4.99$	1.66 ± 1.66	$4.1^{b}\pm0.07$
3Hz-150 sec	$38.44^{b}\pm4.93$	$61.56^{c}\pm4.93$	0.00 ± 0.00	$4.3^{ab}\pm0.07$
4Hz-50 sec	$23.00^{c}\pm4.51$	$77.02^{abc}\pm4.53$	0.00 ± 0.00	$4.1^{b}\pm0.05$
4Hz-150 sec	$14.28^{c}\pm4.03$	$82.64^{ab}\pm5.24$	3.08 ± 3.08	$3.9^{b}\pm0.15$
5Hz-50 sec	$0.00^{d}\pm0.00$	$96.64^{a}\pm2.07$	3.36 ± 2.07	$2.9^{c}\pm0.24$
5Hz-150 sec	$0.00^{d}\pm0.00$	$80.76^{abc}\pm11.79$	19.24 ± 10.45	$3.2^{c}\pm0.17$

Means in different letters in the same column in each day for DMRT test indicate significant differences at 5% level (mean±S.E., n=5).

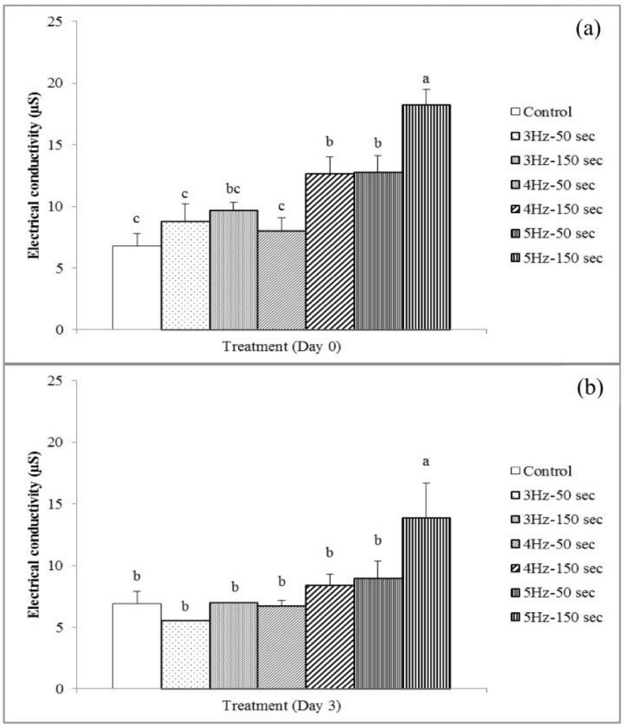

Fig 1. Electrical conductivity of 'Elsanta' strawberries after vibration test at day 0 (a) and day 3 (b). Different letters in treatments for DMRT test indicate significant differences at 5% level (mean±S.E., n=5).

Results and Discussion

The vibration damage by visual evaluation

On the first day of storage (day 0), the vibration tests (3 and 4 Hz at 50 sec) had the highest percentage of undamaged fruits (around 85%) among the treatments ($p<0.05$). At 5 Hz (1.1 g) for 150 sec, there was the greatest number of dry bruises (71%) and wet bruises (13%) ($p<0.05$) while control treatment had not any damage before the vibration test. The lowest severity bruise score by the visual assessment was also

Table 2. Puncture and compression values and fruit weight of 'Elsanta' strawberries at day 0 and 3 after vibration test at 3, 4 and 5 Hz for 50 and 150 sec.

Treatment	Puncture (kg)	Compression (kg)	Fruit weight (g)
Day 0			
Control	0.504±0.013	1.488±0.009	21.43±0.02
3Hz-50 sec	0.524±0.022	1.520±0.050	18.99±1.30
3Hz-150 sec	0.504±0.015	1.510±0.077	20.50±0.38
4Hz-50 sec	0.512±0.027	1.465±0.031	18.99±1.30
4Hz-150 sec	0.467±0.023	1.445±0.035	19.60±0.41
5Hz-50 sec	0.511±0.016	1.470±0.017	18.41±1.26
5Hz-150 sec	0.510±0.027	1.488±0.046	20.63±1.90
Day 3			
Control	0.627^{a}±0.018	1.955^{a}±0.051	19.51±0.45
3Hz-50 sec	0.552^{ab}±0.033	1.609^{b}±0.070	18.41±1.65
3Hz-150 sec	0.507^{bc}±0.087	1.557^{bc}±0.037	18.53±0.25
4Hz-50 sec	0.538^{bc}±0.040	1.541^{bc}±0.085	19.36±0.55
4Hz-150 sec	0.519^{bc}±0.019	1.391^{c}±0.052	19.03±0.17
5Hz-50 sec	0.551^{ab}±0.024	1.541^{bc}±0.040	18.91±0.93
5Hz-150 sec	0.454^{c}±0.033	1.496^{bc}±0.042	18.54±0.77

Means in different letters in the same column in each day for DMRT test indicate significant differences at 5% level (mean±S.E, n=5).

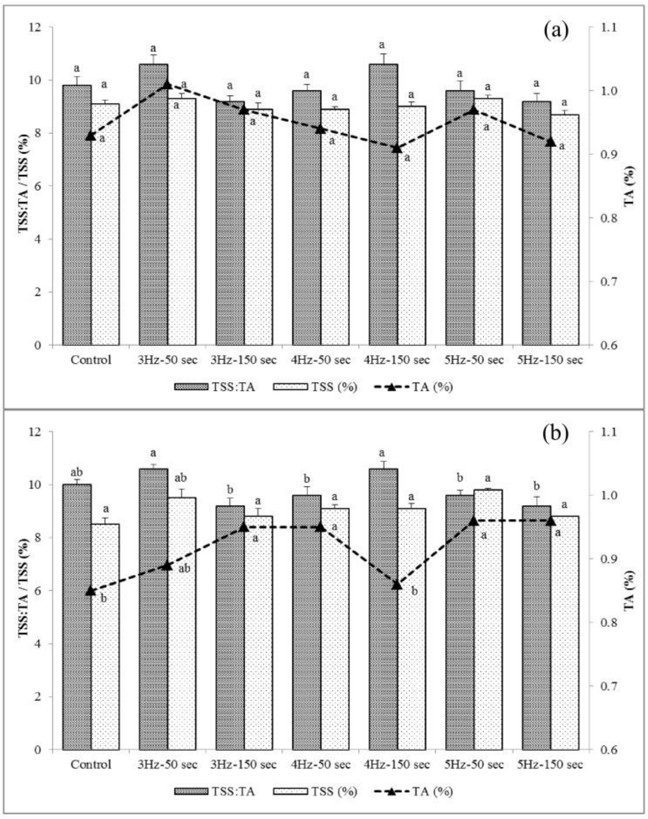

Fig 2. TSS:TA, TSS (%) and TA (%) of 'Elsanta' strawberries after vibration test at day 0 (a) and day 3 (b). Different letters in treatments for DMRT test indicate significant differences at 5% level (mean±S.E., n=5).

Table 3. The correlation coefficient (*r*) between EC value and firmness or severity score of bruise of 'Elsanta' strawberries at day 0 and day 3.

Properties	Severity score	EC
Day 0		
EC	-0.764**	1.000
Puncture	-0.071	-0.221
Compression	0.110	-0.082
Day 3		
EC	-0.571**	1.000
Puncture	-0.206	-0.478**
Compression	0.372*	-0.266

** Correlation is significant at 1% level (n=35).

found in the vibration frequency at 5 Hz (1.1 g for 150 sec) which related to the maximum percentage of bruise (Table 1). Our results are in agreement with Nakamura et al. (2008) report which showed a high correlation value between acceleration level and vibration damage in strawberries (r=0.8660). However, the similar vibration level was reported by Jiang et al. (2001). The vibration level at 5 Hz (1.6 g) for 40 sec was observed not to give damage following visual evaluation in 'Tayonoka' strawberries. In our study, the frequency at 5 Hz (1.1 g) of 150 sec was the critical frequency for the increases of the losses and a reduction of severity score in 'Elsanta' strawberries (Table 1). After storage condition (at 10^{O}C for 3 days), the vibration level at 5 Hz showed no undamaged fruits and that the severity score was significantly lower than at 3 and 4 Hz ($p<0.05$). The percentage range of dry bruise increased rapidly in the vibrated strawberries from 60 to 95% whereas control was found to have around 40% dry bruise (Table 1). In addition, our results showed no rot and mould were observed and agree with the Nakamura et al. (2007) result. The stimulated vibration level at 7 Hz (1 g) for 60 sec showed no increase of bacterial rot on strawberry fruits after storage at 10^{o}C for 4 days. However, the previous as well as our studies were based on the simulated vibration to strawberry damage. In the actual transport for strawberry shipment in Japan, Kojima et al. (1999) stated that the frequencies of vibration levels were 3.35, 7 and 13.5 Hz with acceleration levels (0.02 to 0.19 g) that caused strawberry damage. Therefore, our findings support previous studies that the range of vibration frequencies and accelerations to strawberry damage was approximately 3.35 to 13.5 Hz with 0.02 to 1.1 g, respectively.

Electrical conductivity

The electrical conductivity of 'Elsanta' strawberries was greater at 5 Hz (1.1 g) for 150 sec (18.2 µS) as compared to the control treatment, 3 Hz (0.4 g) and 4 Hz (0.8 g) ($p<0.05$). Undamaged strawberry fruits after harvesting had the lowest electrical conductivity level and there was little difference at the low vibration level of 3 Hz and 4 Hz for 50 sec (Fig 1). The highest frequency and time (5 Hz for 150 sec) also had the highest dry and wet bruises and the lowest severity score (Table 1). After storage condition for 3 days, the conductivity values decreased around 20 to 35% (Fig 1B). Jiang et al. (2001) reported that the conductivity of 'Toyonoka' strawberry greatly reduced after storage at 25^{o}C for 3 days. In our study, the highest vibration level (5 Hz for 150 sec) gave a significant ion leakage compared to other treatments after immediate test and storage (Fig 1). These observations agree with previous research that the simulated vibration test of 'Selva' strawberries at the 5 to 10 Hz (0.6 g) range for 1800 sec caused the maximum damage (Fischer et al., 1992).

In the comparison between 5 Hz (1.1 g) and 3 Hz (0.4 g) or 4 Hz (0.8 g) for 50 sec after storage, there was no a significant difference in EC value ($p>0.05$). Jiang et al. (2001) reported that at the vibration frequency of 5 Hz with a 3-dimensional vibrator at 1.4 g for 20 sec or 1.2 g for 40 sec there was no change in the EC value. Although the same acceleration level in this study could not be controlled for all frequency levels (3 to 5 Hz). Our acceleration condition in the range applied (0.4 to 1.1 g) is in agreement with previous studies (0.6 to 1.4 g) (Fischer et al., 1992; Jiang et al., 2001) The results of this study and previous research showed that the simulated vibration condition on the conductivity (undamaged fruits) is suggested in the range of frequency 5 to 10 Hz with acceleration (0.6 to 1.4 g) for over 40 sec.

Fruit firmness and fruit weight

Fruit firmness was measured by puncture and compression tests and was found to not show statistically significant differences after vibration condition ($p>0.05$). After cool storage for 3 days, control treatment had the highest puncture and compression values ($p<0.05$) (Table 2). Fischer et al. (1992) found in vibration test at 2-30 Hz (0.6 g) for 1800 sec that there was no effect on the firmness measurement with shear force test. The strawberry firmness also depends on fruit size and the small fruits were firmer than large ones (Døving and Måge, 2002). Our result showed that the fruit weight had no a significant difference on firmness with the range size (18.5 to 21.4 g per fruit) ($p>0.05$) (Table 2).

Total soluble solids (TSS), titratable acidity (TA) and TSS: TA ratio

The contents of TSS, TA and TSS:TA ratio in 'Elsanta' strawberries were around 9%, 0.93% and 9.5:1, respectively (Fig 2). TSS and TSS: TA ratio levels of our testing fruits were higher than the previous study (Strum et al., 2003). Our results also agreed with that reported from general strawberry cultivars. The minimum TSS and maximum TA levels for an acceptable flavour of strawberry were recommended at 7% and 0.8%, respectively (Kader, 1999). After the vibration test and storage, there were no the significant differences in TSS, TA and TSS;TA ratio. TSS content did not change statistically during storage condition ($p>0.05$) (Fig 2). Our results support Izumi et al. (1999) research into vibration of strawberries which had no effect on TSS and TA contents. In contrast, Kojima et al. (1999) observed that TSS content reduced around 5% after simulated vibration test and storage (5^{o}C) for 12 hours. While Chen et al. (2011) found that TA content in mulberry fruit, also a non-climacteric fruit, decreased during storage. Ornela-Paz et al. (2013) found that there was no significant correlation between firmness of 'Albion' strawberries and TSS content.

The correlation coefficient (r) between EC value and firmness or severity score of bruise

The EC value significantly correlated with severity score of bruises at day 0 and day 3 (r=-0.764 and r= -0.571) ($p<0.01$) whereas puncture and compression tests gave no correlation with severity score (Table 3). Interestingly, the EC value in the present study showed more accuracy than that firmness tests for damage evaluation.

Materials and Methods

Plant materials

'Elsanta' strawberry with A+ grade and crown diameter ≥ 15 mm was provided by RW Walpole Ltd, UK. Two hundred strawberry plants were grown in the greenhouse at Writtle College, Chelmsford. The strawberry cultivations were conducted from 10^{th} February to 27^{th} May in 2014. Only harvested marketable grade fruit was used (a uniform size and fruit weight from 18 to 21 g, full red colour with TSS > 8%). Strawberry fruits were packed in 250 g in polyethylene terephthalate (PET) vented punnets (105 x 170 x 60 mm). Packed fruits were transported to the postharvest laboratory within 2 hours of harvest. The punnet was cooled by room cooling within 4 hours to the pulp temperature of 7.0°C (±1°C). The cooled punnet was top sealed with commercial plastic film with 6 perforations of 8 mm diameter (Adare Advantage Ltd).

Vibration test

Vibration tests were carried out at three frequency levels at 3, 4, and 5 Hz for 50 and 150 sec by orbital shaker at amplitude 16 mm (Stuart SSL1, UK). Five punnets (replicates) were conducted in vibration test. The acceleration (g) level of the orbital shaker was measured by spectral vibration logger SVR101 (MadgeTech, USA). The frequency and acceleration levels of the vibration test were 3 Hz (0.4 g), 4 Hz (0.8 g), and 5 Hz (1.1 g). The acceleration level of this study was determined based on the previous studies presented by Fischer et al. (1992) and Jiang et al. (2001).

Quality determination

Strawberry quality was determined immediately after the vibration test (day 0) and after storage at 10±1°C and relative humidity (RH) at 70% (±5%RH) for 3 days.

Assessment of percentage of quality category and severity bruise score

Percentage of each quality category was calculated from the number of fruits in each category of damage (undamaged, dry and wet bruises). The individual severity of bruises was scored and modified from undamaged level (score 5) to very severely damage level and mould formation (score 1) according to the rating scale, described by Fischer et al. (1992)

Measurement of electrical conductivity

Electrical conductivity (EC) was evaluated and adapted using the method of Jiang et al. (2001). Five fruits randomly selected from each punnet were immersed in a 500 ml of distilled water at 25°C for 10 min. The sample temperature in distilled water was controlled using the water bath (Phillip Harris, UK). The immersed fruits were gently stirred for 5 sec before the determination of EC test was recorded with a handheld conductivity meter (CyberScan CON 110, Eutech Instruments, USA) and expressed as µS.

Fruit weight and firmness evaluation

Fruit firmness in each test (3 fruits in each punnet) was determined from the maximum peak of force (kg) using fruit texture analyser GS-20 (GüSS Manufacturing (Pty) Ltd, South Africa). The speed of measurement was at 10 mm/sec with a 8 mm cylinder probe (puncture test) and also a second test using a 42 mm compression platens (compression test) for 8.9 mm (a measured distance). The fruit weight of three fruits from each punnet was randomly measured with a digital balance (Mettler PE 600, Precisa Balances Limited, UK).

Measurements of total soluble solids (TSS), titratable acidity (TA) and TSS: TA ratio

Six strawberries in each punnet were cut into four identical portions which were randomly representative sampled for TSS (%), TA (%), and TSS:TA ratio. The strawberry juice was measured TSS with a digital pocket refractometer (PAL-1, Atago, Japan). Titratable acidity (TA) was measured by titration of strawberry juice with 0.1 M sodium hydroxide and expressed as citric acid (%w/w) (AOAC, 1990).

Statistical analysis

The experimental design was performed using a completely randomized design with 5 replications. Analyses of variance and correlation coefficient (r) were performed using SPSS version 16.0. Duncan's multiple range test (DMRT) were calculated at 5% level of significance ($p<0.05$). The correlation coefficient (r) between EC value and firmness or severity score of bruise was calculated by Pearson's correlation at 1% level of significance ($p<0.01$).

Conclusion

The vibration level at 5 Hz for 150 sec provided significantly the greater bruise and conductivity values as compared to 3 and 4 Hz. EC values of strawberry bruise decreased with an increasing storage at 10°C for 3 days. Bruise symptom did not affect TSS, TA and TSS:TA ratio. The evaluation of electrical conductivity in 'Elsanta' strawberry bruises had a high negative correlation with the severity score of bruises at $P\leq0.01$ while there was no a correlation between severity score and firmness tests. The study suggests that EC could be applied and used to provide a rapid and accurate method to assess strawberry bruises during postharvest handling and transportation.

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References

AOAC (1990) Official methods of analysis of the Association of Official Analytical Chemists, 15th ed. Association of Official Analytical Chemists, Arlington, Virginia, pp: 1058-1059.

Chen Z, Zhu C, Han Z (2011) Effects of aqueous chlorine dioxide treatment on nutritional components and shelf-life of mulberry fruit (*Morus alba* L.). J Biosci Bioeng. 111: 675-681.

Department for Environment Food and Rural Affairs (2013) Basic horticultural statistics dataset. www.gov.uk/government/publications/basic-horticultural-statistics (Access 20 April 2015).

Døving A, Måge F (2002) Methods of testing strawberry fruit firmness. Acta Agr Scand. 51: 43-51.

Ferreira MD, Sargent SA, Brecht JK, Chandler CK (2008) Strawberry fruit resistance to simulated handling. Sci Agric. 65: 490-495.

Fischer D, Craig WL, Watada AE, Douglas W, Ashby BH (1992) Simulated in-transit vibration damage to packaged fresh market grapes and strawberries. Appl Eng Agric. 8: 363-366.

Fresh Produce Journal (2012) Refresh directory 2012: an essential resource for the fresh produce industry, London.

Izumi T, Toshihiro T, Hatsuko M, Massanobu T, Yan LJ, Takayuki K, Hideaki O (1999) Effect of vibration by simulated transportation on respiration rate and quality of strawberry fruits. Food Pres Sci. 25: 15-20.

Jiang Y, Shina T, Nakamura N, Nakahara A (2001) Electrical conductivity evaluation of postharvest strawberry damage. J Food Sci. 66: 1392-1395.

Kader AA (1999) Fruit maturity, ripening, and quality relationships. Acta Hort. 485: 203-208.

Kojima T, Liu JY, Fujita S, Inaba S, Tanaka M, Tatara I (1999) Analysis of vibration and its effects on strawberries during highway transport. Journal of SASJ. 29: 197-203.

Ministry of Agriculture, Fisheries, and Food (MAFF) (1996) Common standards of quality for strawberry. In: EC Quality standards for horticultural produce. MAFF Publications, London, pp: 9-1-9-4.

Nakamura N, Umehara H, Nei D, Okadome H, Ishikawa Y, Nakano K, Maezawa S, Shina T (2008) Effect of package conditions on the damage of strawberries. Journal of SASJ. 6: 1-8.

Nakamaru N, Inatsu Y, Kawamoto S, Okadome H, Nakano K, Maezawa S, Shiina T (2007) Effect of vibration on the bacterial growth on strawberry fruits. J Food Agric Environ. 5: 44-48.

Organisation for Economic Co-Operation and Development (OECD) (2005) International Standardisation of fruit and vegetables, Strawberries. http://www.oecd.org/tad/code/46597780.pdf (Access 27 April 2015).

Ornelas-Paz JDJ., Yahia EM, Ramírez-Bustamante N, Pérez-Martínez JD, Escalante-Minakata MDP, Ibarra-Junquera V, Acosta-Muñiz C, Guerrero-Prieto V, Ochoa-Reyes V (2013) Physical attributes and chemical composition of organic strawberry fruit (*Fragaria* x *ananassa* Duch, *Cv.* Albion) at six stages of ripening. Food Chem. 138: 372-381.

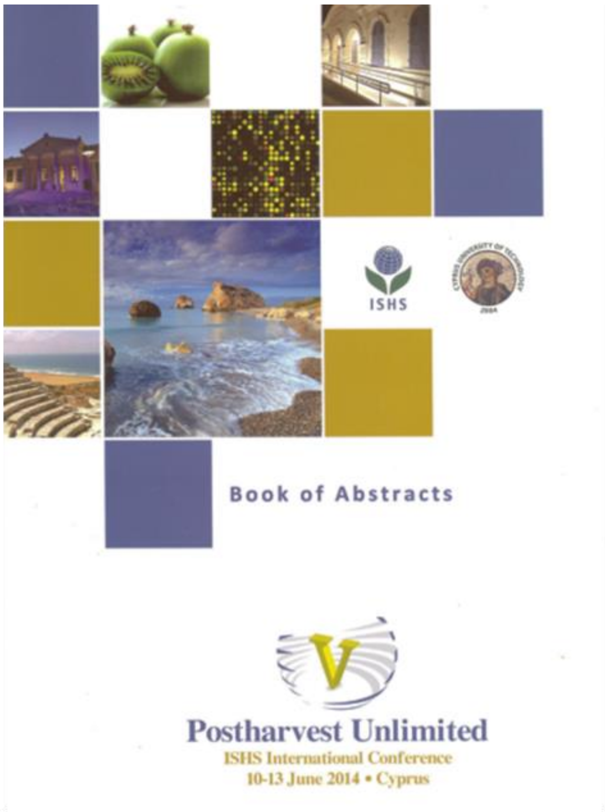
Pelletier W, Brecht JK, Nunes MCN, Émond JP (2011) Quality of strawberries shipped by truck from California to Florida as influenced by postharvest temperature management practices. Horttechnology. 21: 482-493.

Smith JP, Zagory D, Ramaswamy HS (2005) Packaging of fruits and vegetables. In: Barrett DM, Somogyi L, Ramaswamy H (ed) Processing fruits: Science and Technology, 2nd edn. CRC Press, Florida.

Sturm K, Koron D, Stampar F (2003) The composition of fruit of different strawberry varieties depending on maturity stage. Food Chem. 83: 417-422.

Terry LA, Mena C, Williams A, Whitehead P (2011) Fruit and vegetable resource maps: Mapping fruit and vegetable waste through the retail and wholesale supply chain. WRAP, RC008.

Appendix 4.3: The poster presentation: Chaiwong, S. and Bishop, C.F.H. (2014) 'Impact and vibration damage to 'Elsanta' strawberries in punnet by electrical conductivity evaluation', *Book of Abstracts of Postharvest Unlimited ISHS International Conference*, Cyprus, 10-13 June 2014, 121.



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Impact and vibration damage to 'Elsanta' strawberries in punnet by electrical conductivity evaluation

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'Elsanta' strawberries were packed in standard supermarket 227 g and 350 g polyethylene terephthalate (PET) punnets for impact and vibration tests, respectively. The impact test was measured by a simple drop test of the punnet at 0, 500, and 1000 mm onto mild steel. Vibration tests were carried out at three frequency levels at 3, 4 and 5 Hz for 5 min. After impact and vibration tests, strawberries in the punnets were evaluated immediately for electrical conductivity, percentage of losses (undamaged, dry and wet bruises), firmness and severity of bruises. The electrical conductivity values and percentage of the wet bruise showed an increase with drop height or frequency level and were significantly higher for the more severe tests than for the more gentle treatment ($P<0.05$). In the impact test, the conductivity values were significantly correlated with firmness values ($r= -0.784$). The conductivity values also were highly associated with severity of bruises ($r= -0.934$) and showed higher correlation ($r=0.820$) than for firmness. Results indicated that the electrical conductivity evaluation in impact and vibration tests can be used as a rapid assessment method to assess strawberry bruises during handling and transportation.

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